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Chang et al.

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(45) **Date of Patent: *Feb. 25, 2003**

(54) **HIGH-THROUGHPUT, LOW-LATENCY NEXT GENERATION INTERNET NETWORKS USING OPTICAL LABEL SWITCHING AND HIGH-SPEED OPTICAL HEADER GENERATION, DETECTION AND REINSERTION**

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(73) Assignee: **The Regents of the University of California**, Oakland, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **09/339,995**

(22) Filed: **Jun. 25, 1999**

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/118,437, filed on Jul. 17, 1998, now Pat. No. 6,111,673.
(60) Provisional application No. 60/104,443, filed on Oct. 16, 1998.

(51) **Int. Cl.**[7] **H04J 14/02**
(52) **U.S. Cl.** **359/124**; 359/123; 359/128; 370/352; 370/392; 370/471
(58) **Field of Search** 359/123–124, 359/128, 135; 370/352, 355–356, 392, 471

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(57) **ABSTRACT**

An optical signaling header technique applicable to optical networks wherein packet routing information is embedded in the same channel or wavelength as the data payload so that both the header and data payload propagate through network elements with the same path and the associated delays. The header routing information has sufficiently different characteristics from the data payload so that the signaling header can be detected without being affected by the data payload, and that the signaling header can also be removed without affecting the data payload. The signal routing technique can overlaid onto the conventional network elements in a modular manner using two types of applique modules. The first type effects header encoding and decoding at the entry and exit points of the data payload into and out of the network; the second type effects header detection at each of the network elements.

35 Claims, 14 Drawing Sheets

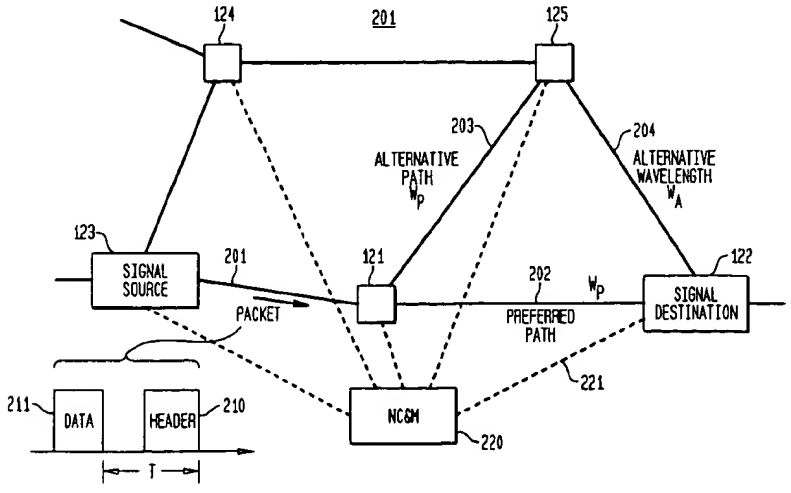

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FIG. 1

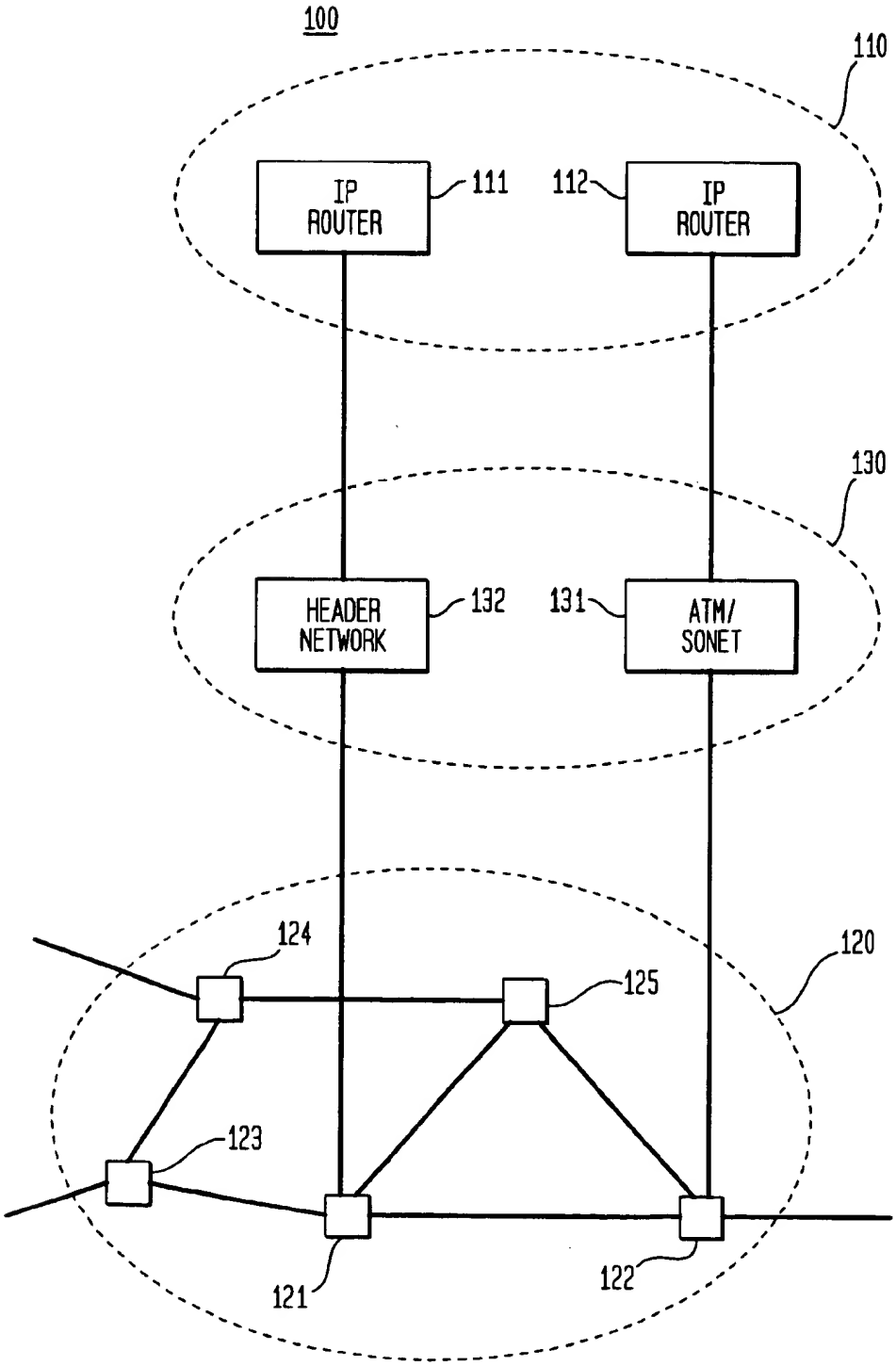

100
110
IP ROUTER
111
112
IP ROUTER
130
HEADER NETWORK
132
131
ATM/ SONET
120
124
125
123
121
122

FIG. 2

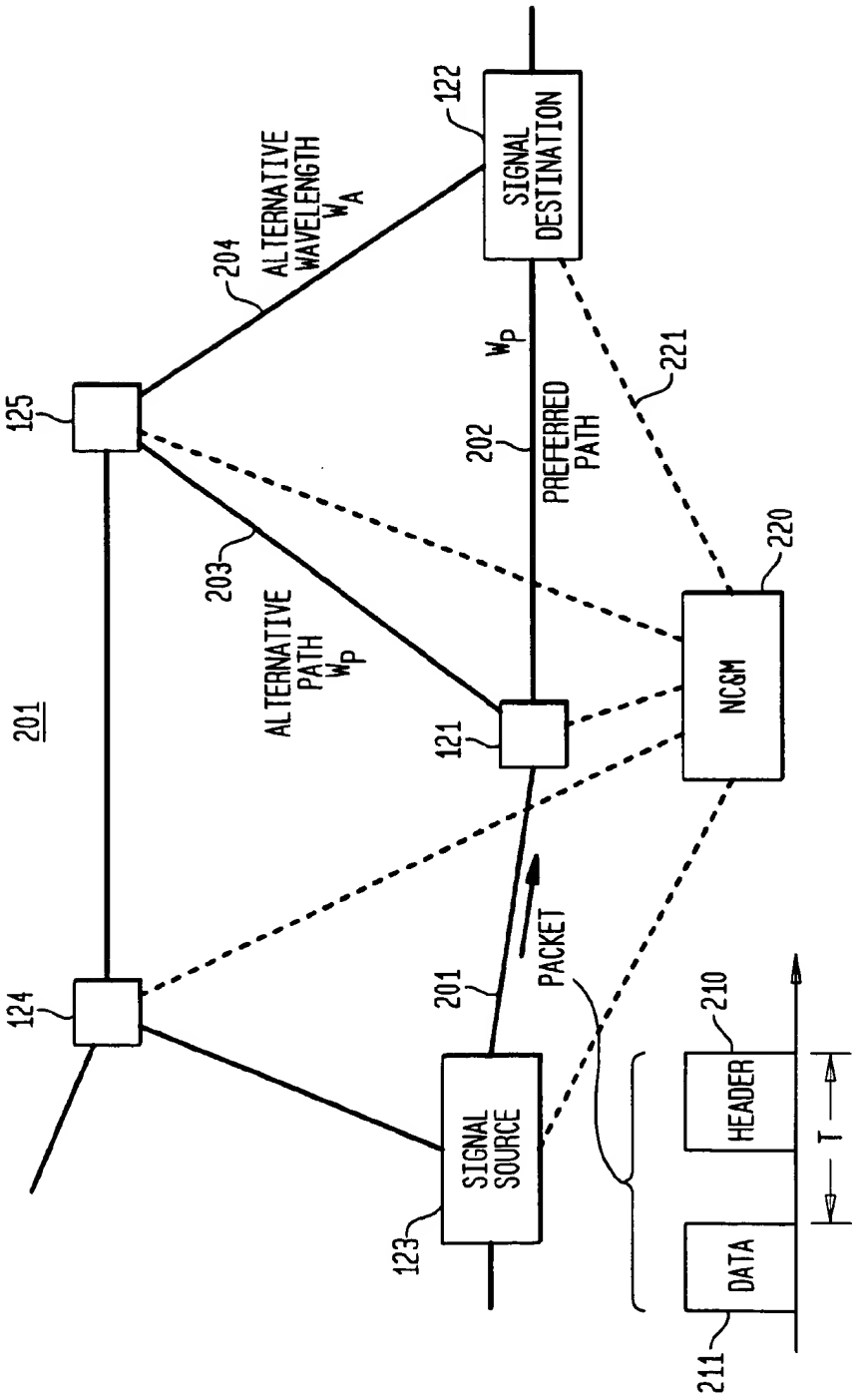

SIGNAL DESTINATION
122
ALTERNATIVE WAVELENGTH W_A
204
W_P
PREFERRED PATH
202
221
125
203
ALTERNATIVE PATH W_P
220
NC&M
201
121
124
PACKET
201
210
HEADER
SIGNAL SOURCE
123
DATA
211
T

FIG. 3

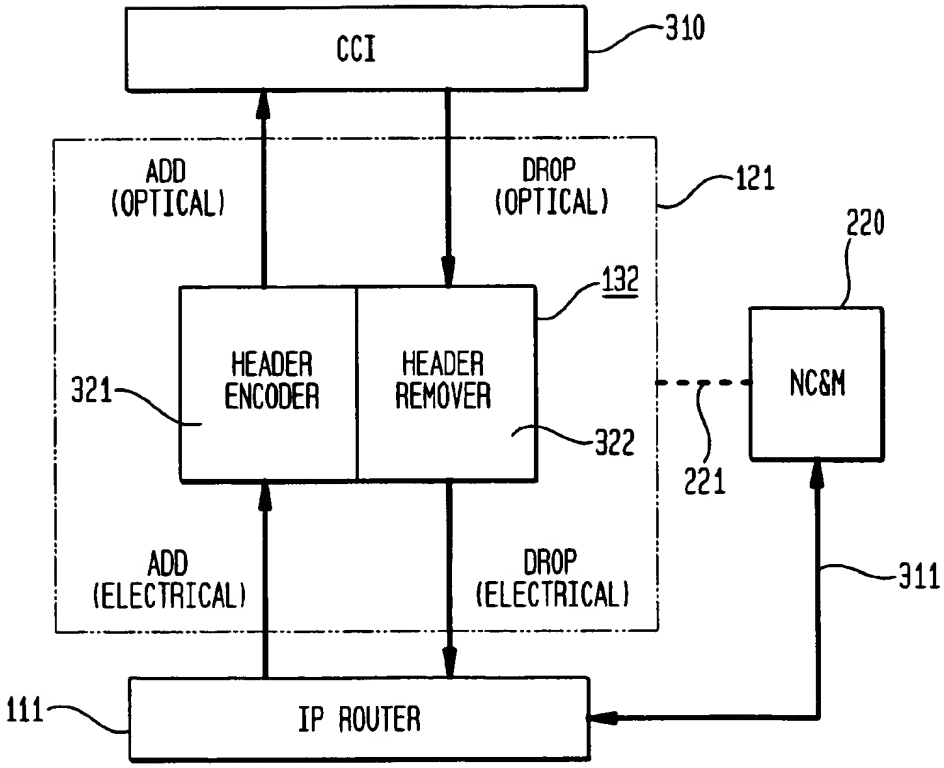
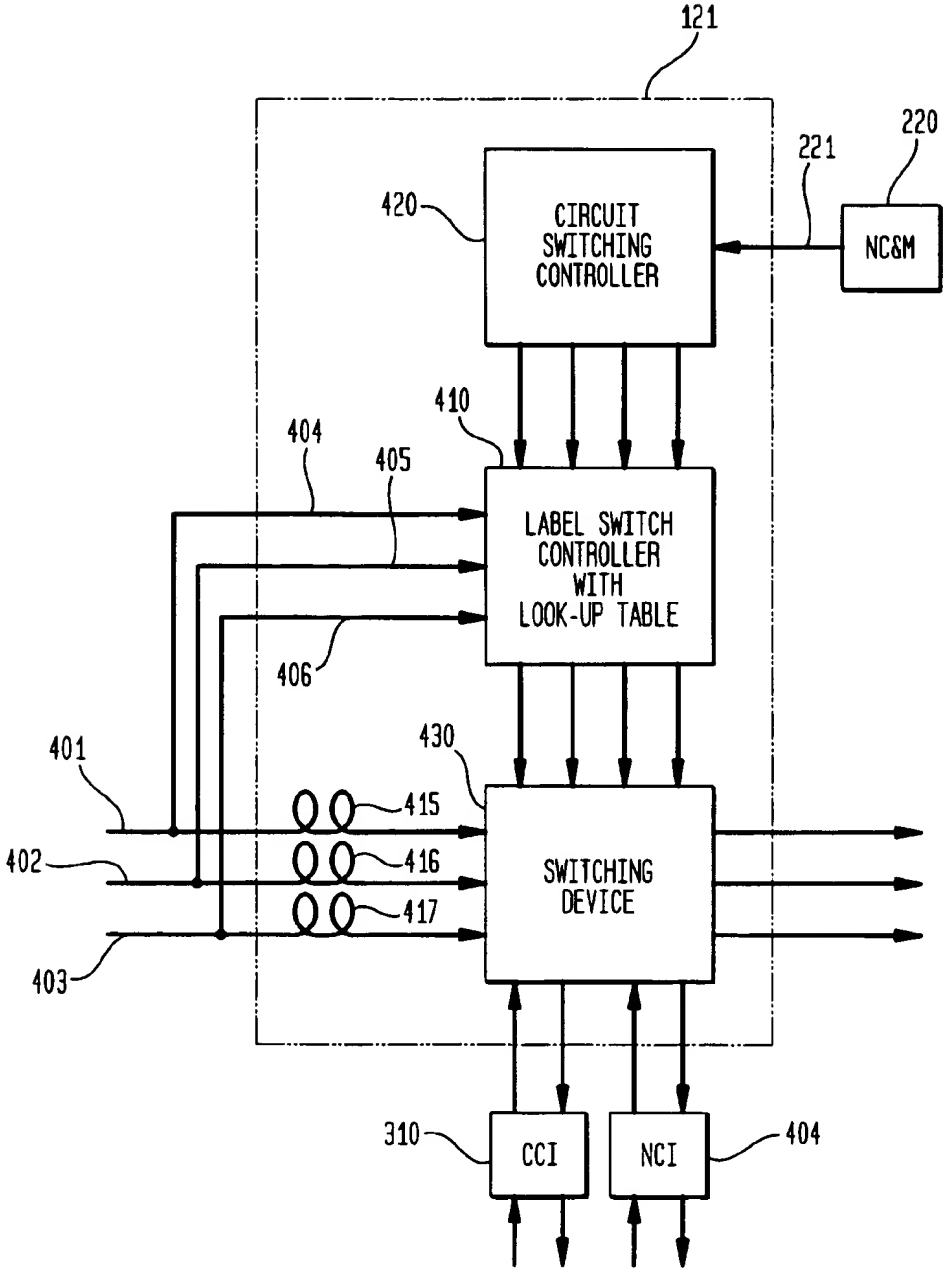

CCI
310
ADD
(OPTICAL)
DROP
(OPTICAL)
121
220
132
HEADER
ENCODER
HEADER
REMOVER
321
322
NC&M
221
ADD
(ELECTRICAL)
DROP
(ELECTRICAL)
311
111
IP ROUTER

FIG. 4


121
220
221
420
CIRCUIT SWITCHING CONTROLLER
NC&M
410
404
405
LABEL SWITCH CONTROLLER WITH LOOK-UP TABLE
406
430
401
415
402
416
417
403
SWITCHING DEVICE
310
CCI
NCI
404

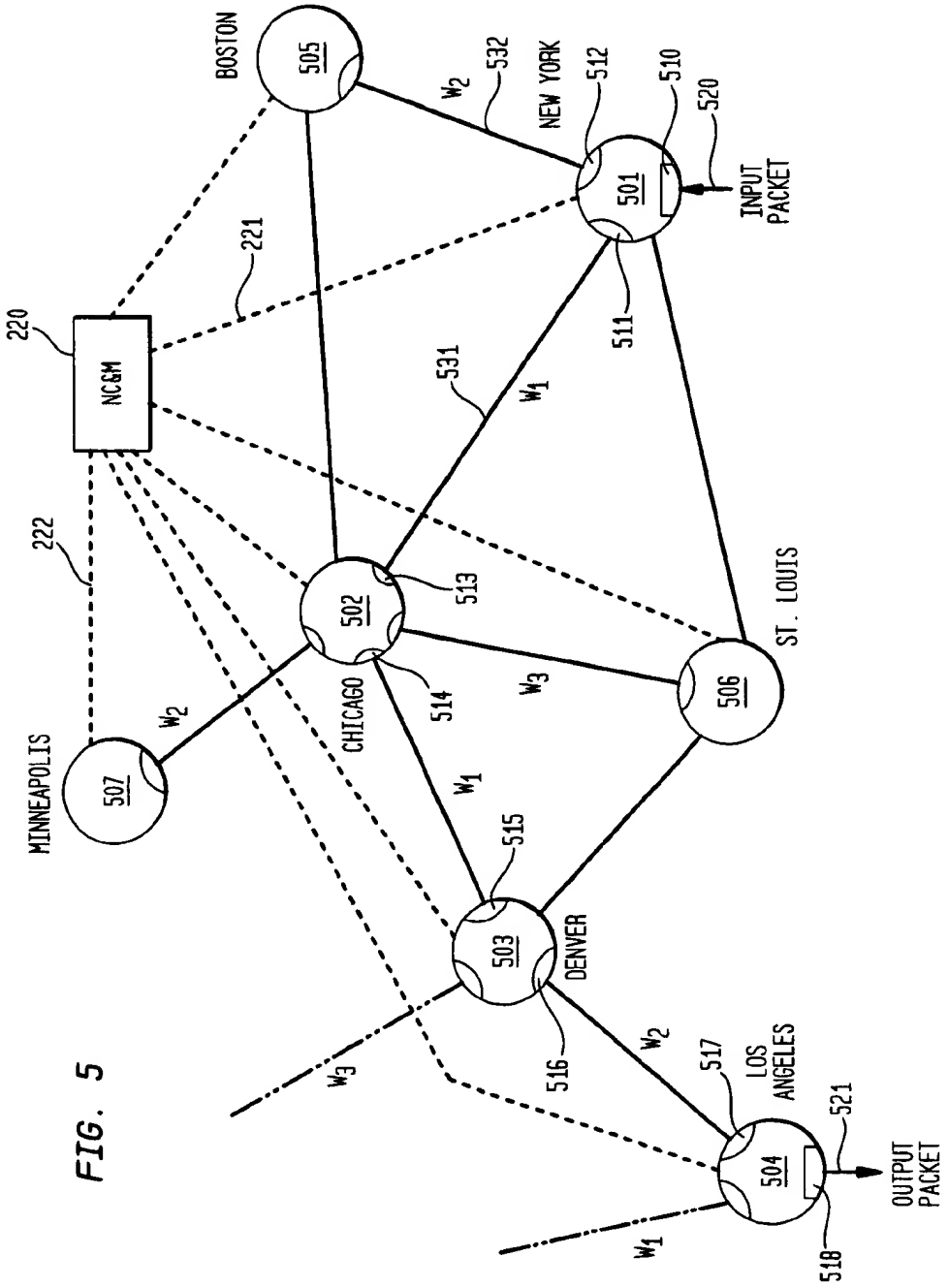
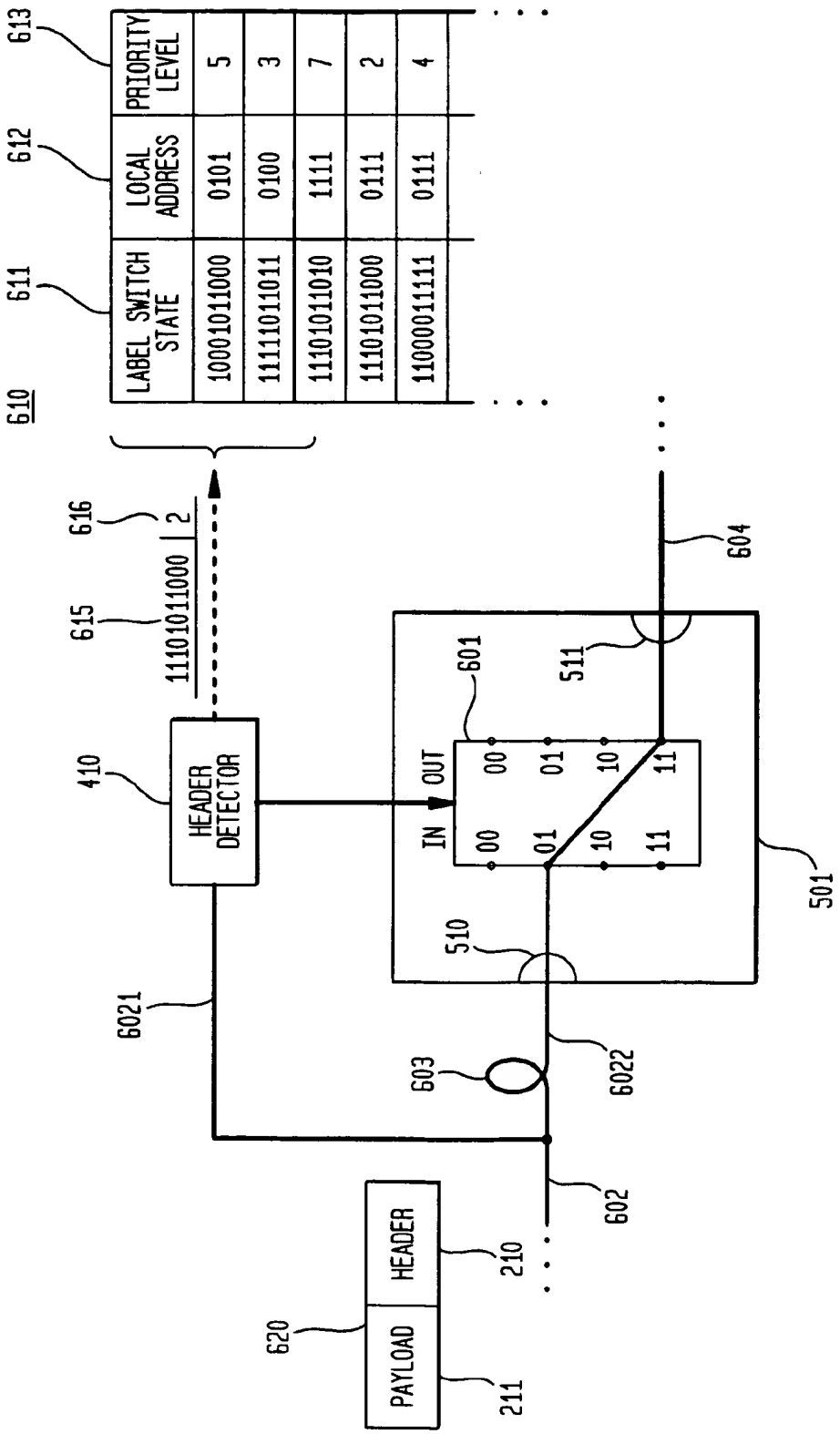

BOSTON
505
532
NEW YORK
512
510
520
INPUT PACKET
501
221
220
NCGM
511
531
W1
222
502
513
ST. LOUIS
506
CHICAGO
514
W3
W2
MINNEAPOLIS
507
W1
515
503
DENVER
W3
516
W2
517
LOS ANGELES
521
504
OUTPUT PACKET
W1
518

FIG. 5

FIG. 6


610
611
LABEL SWITCH STATE
612
LOCAL ADDRESS
613
PRIORITY LEVEL
10001011000
0101
5
11111011011
0100
3
11101011010
1111
7
11101011000
0111
2
11000011111
0111
4
616
2
615
11101011000
410
HEADER DETECTOR
601
IN
OUT
00
01
10
11
501
511
510
604
6021
6022
603
602
620
HEADER
PAYLOAD
210
211

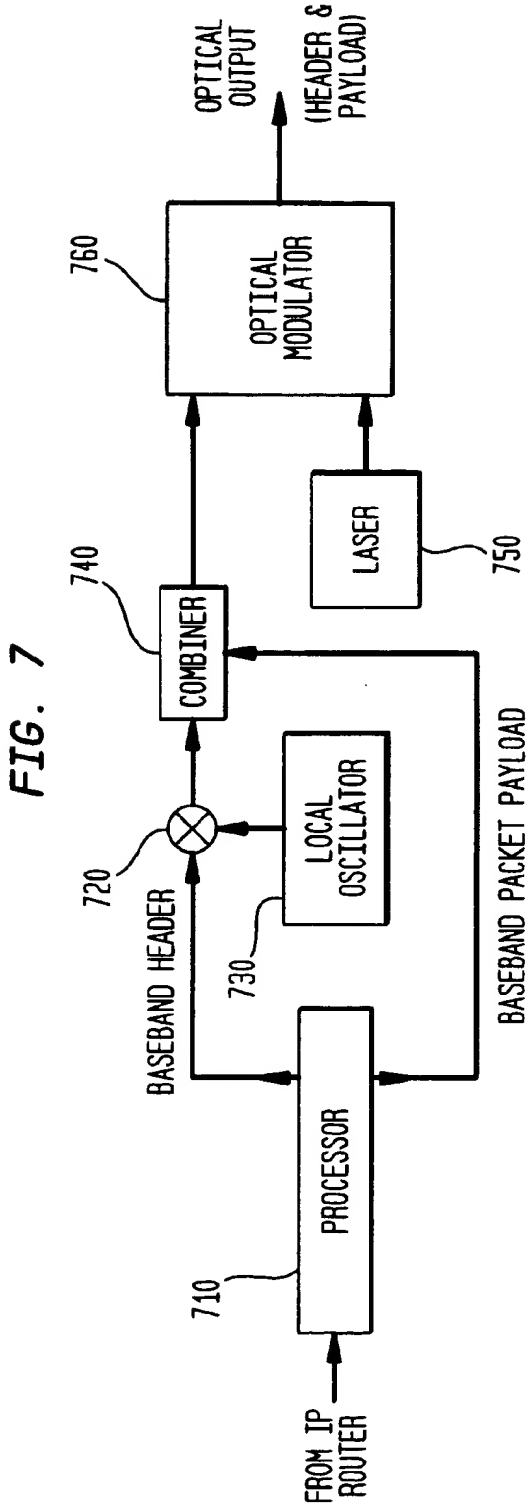

OPTICAL OUTPUT
(HEADER & PAYLOAD)
760
OPTICAL MODULATOR
740
COMBINER
LASER
750
720
LOCAL OSCILLATOR
730
BASEBAND HEADER
BASEBAND PACKET PAYLOAD
710
PROCESSOR
FROM IP ROUTER

FIG. 7

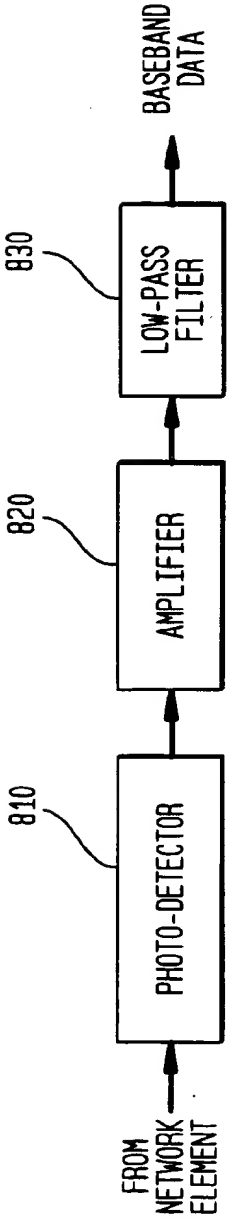

BASEBAND DATA
830
LOW-PASS FILTER
820
AMPLIFIER
810
PHOTO-DETECTOR
FROM NETWORK ELEMENT

FIG. 8

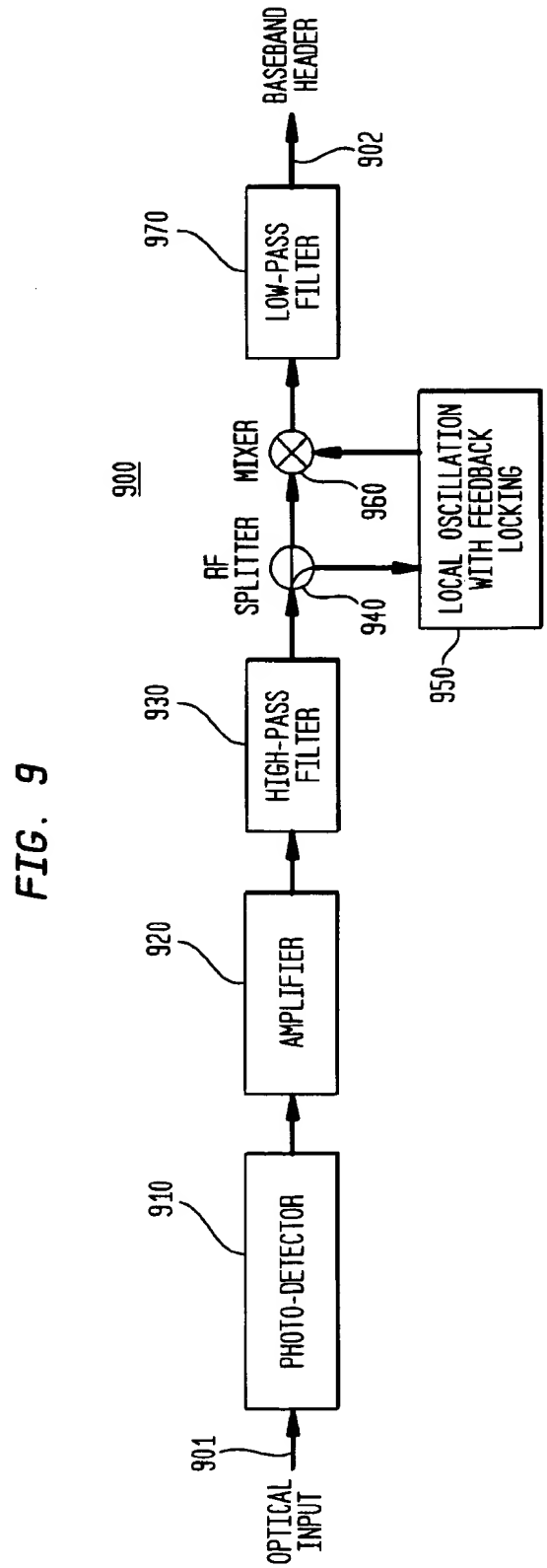

BASEBAND HEADER
902
970
LOW-PASS FILTER
900
MIXER
960
RF SPLITTER
940
LOCAL OSCILLATION WITH FEEDBACK LOCKING
950
930
HIGH-PASS FILTER
920
AMPLIFIER
910
PHOTO-DETECTOR
901
OPTICAL INPUT

FIG. 9

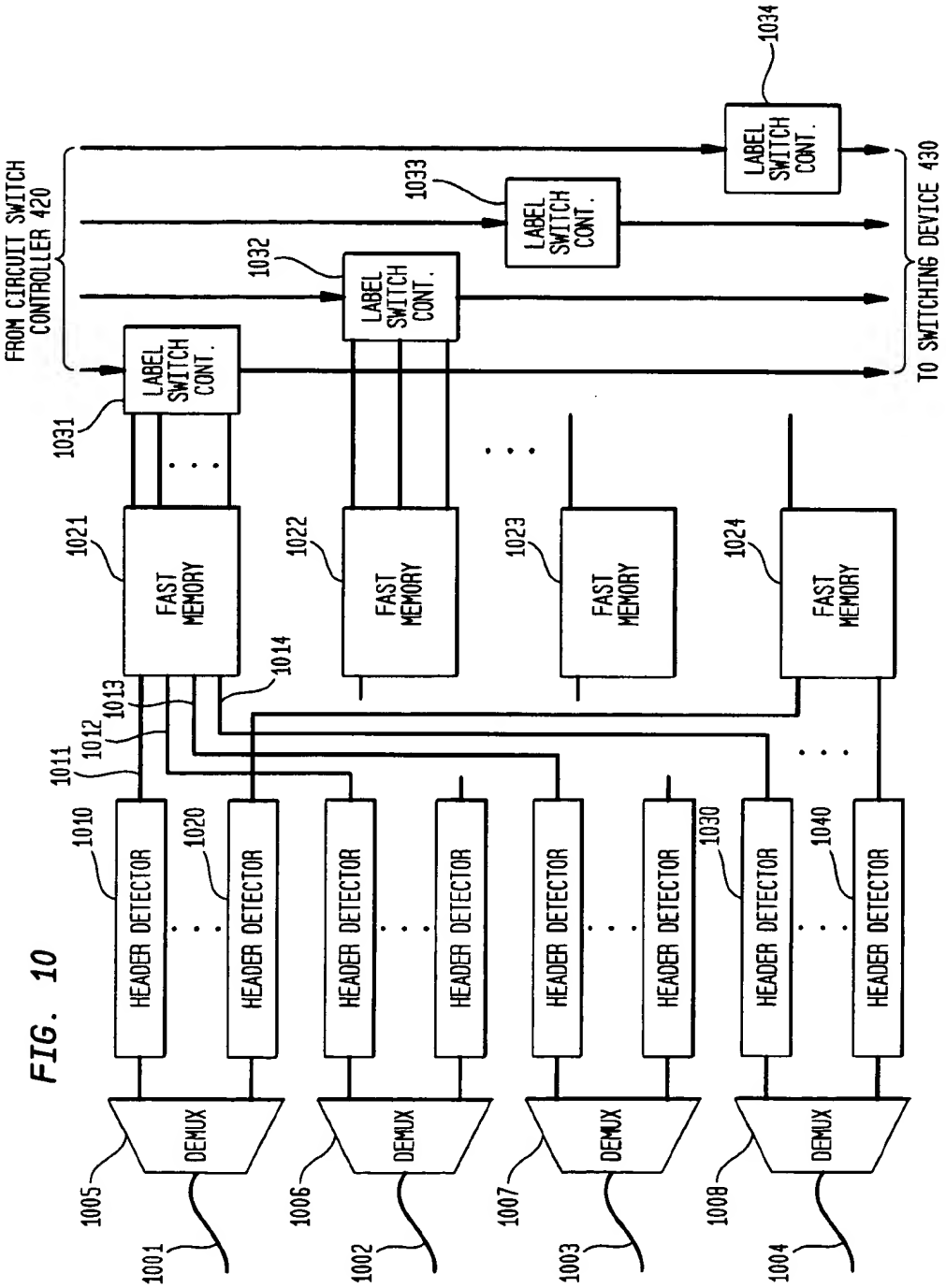
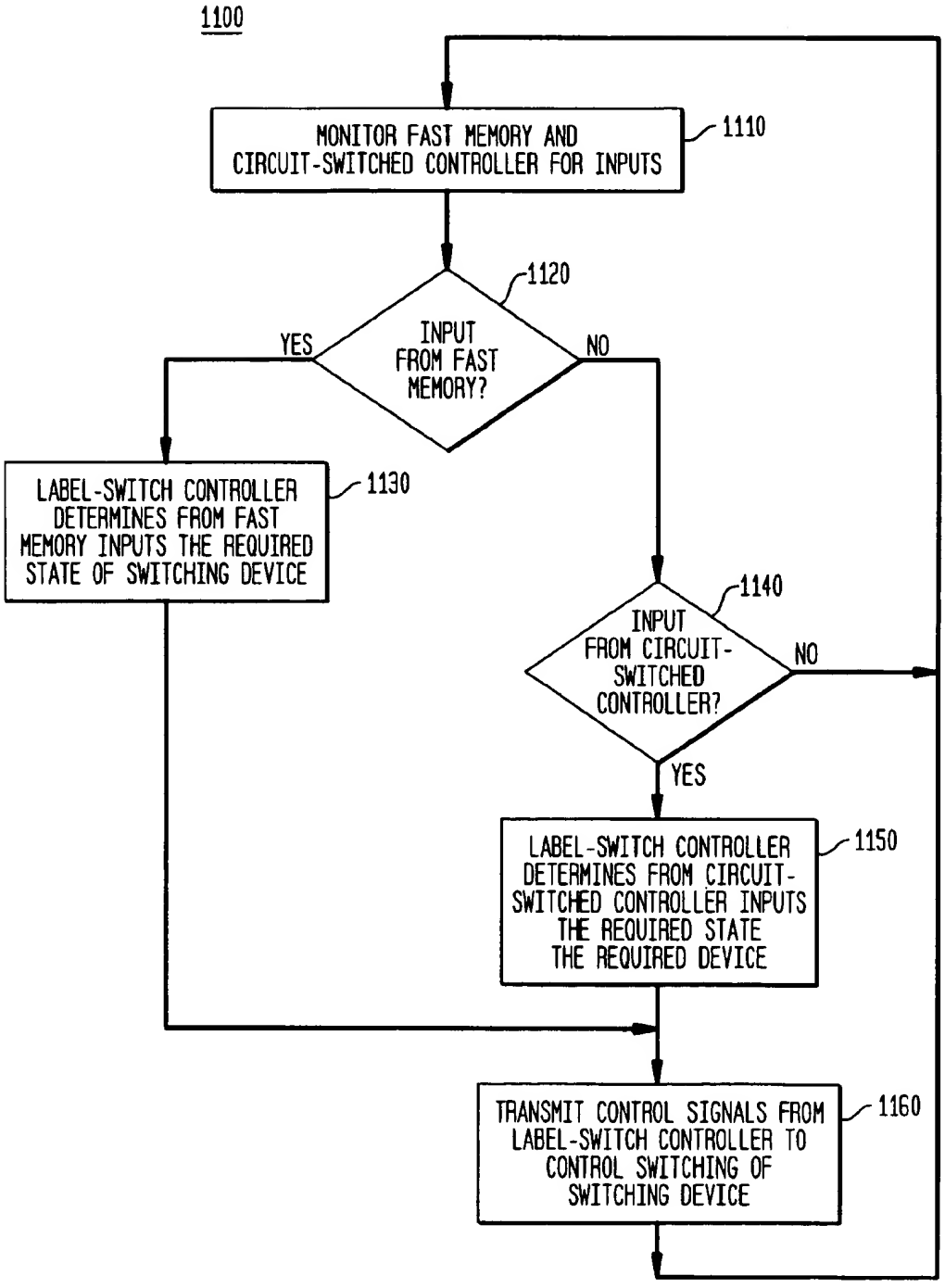

FROM CIRCUIT SWITCH CONTROLLER 420
TO SWITCHING DEVICE 430
LABEL SWITCH CONT.
1031
1032
1033
1034
FAST MEMORY
1021
1022
1023
1024
1011
1012
1013
1014
HEADER DETECTOR
1010
1020
1030
1040
DEMUX
1005
1006
1007
1008
1001
1002
1003
1004

FIG. 10

FIG. 11


1100
MONITOR FAST MEMORY AND CIRCUIT-SWITCHED CONTROLLER FOR INPUTS
1110
1120
INPUT FROM FAST MEMORY?
YES
NO
LABEL-SWITCH CONTROLLER DETERMINES FROM FAST MEMORY INPUTS THE REQUIRED STATE OF SWITCHING DEVICE
1130
1140
INPUT FROM CIRCUIT-SWITCHED CONTROLLER?
NO
YES
LABEL-SWITCH CONTROLLER DETERMINES FROM CIRCUIT-SWITCHED CONTROLLER INPUTS THE REQUIRED STATE THE REQUIRED DEVICE
1150
TRANSMIT CONTROL SIGNALS FROM LABEL-SWITCH CONTROLLER TO CONTROL SWITCHING OF SWITCHING DEVICE
1160

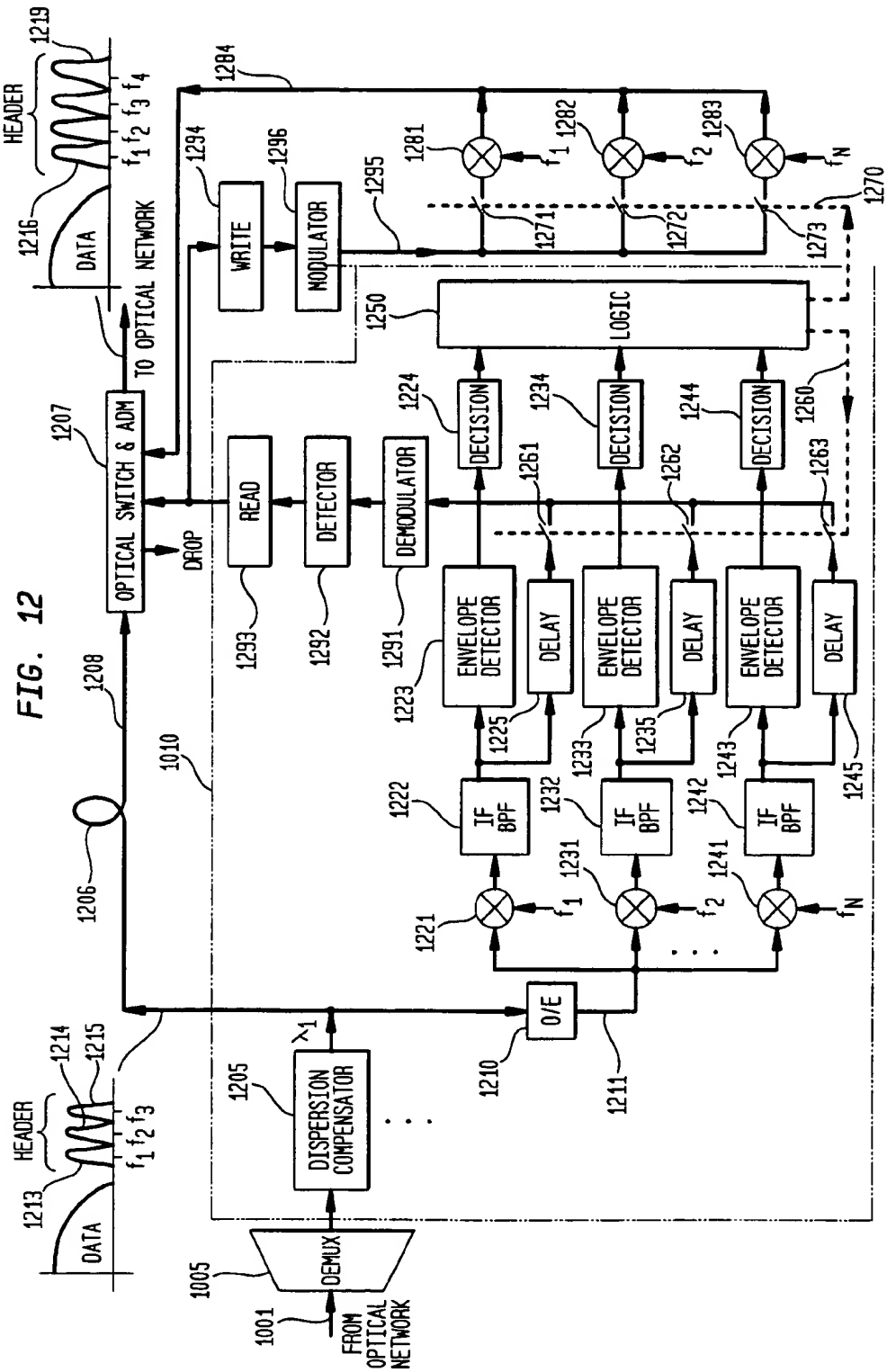

HEADER
DATA
TO OPTICAL NETWORK
WRITE
MODULATOR
LOGIC
DECISION
OPTICAL SWITCH & ADM
DROP
READ
DETECTOR
DEMODULATOR
ENVELOPE DETECTOR
DELAY
IF BPF
O/E
DISPERSION COMPENSATOR
DEMUX
FROM OPTICAL NETWORK

FIG. 12

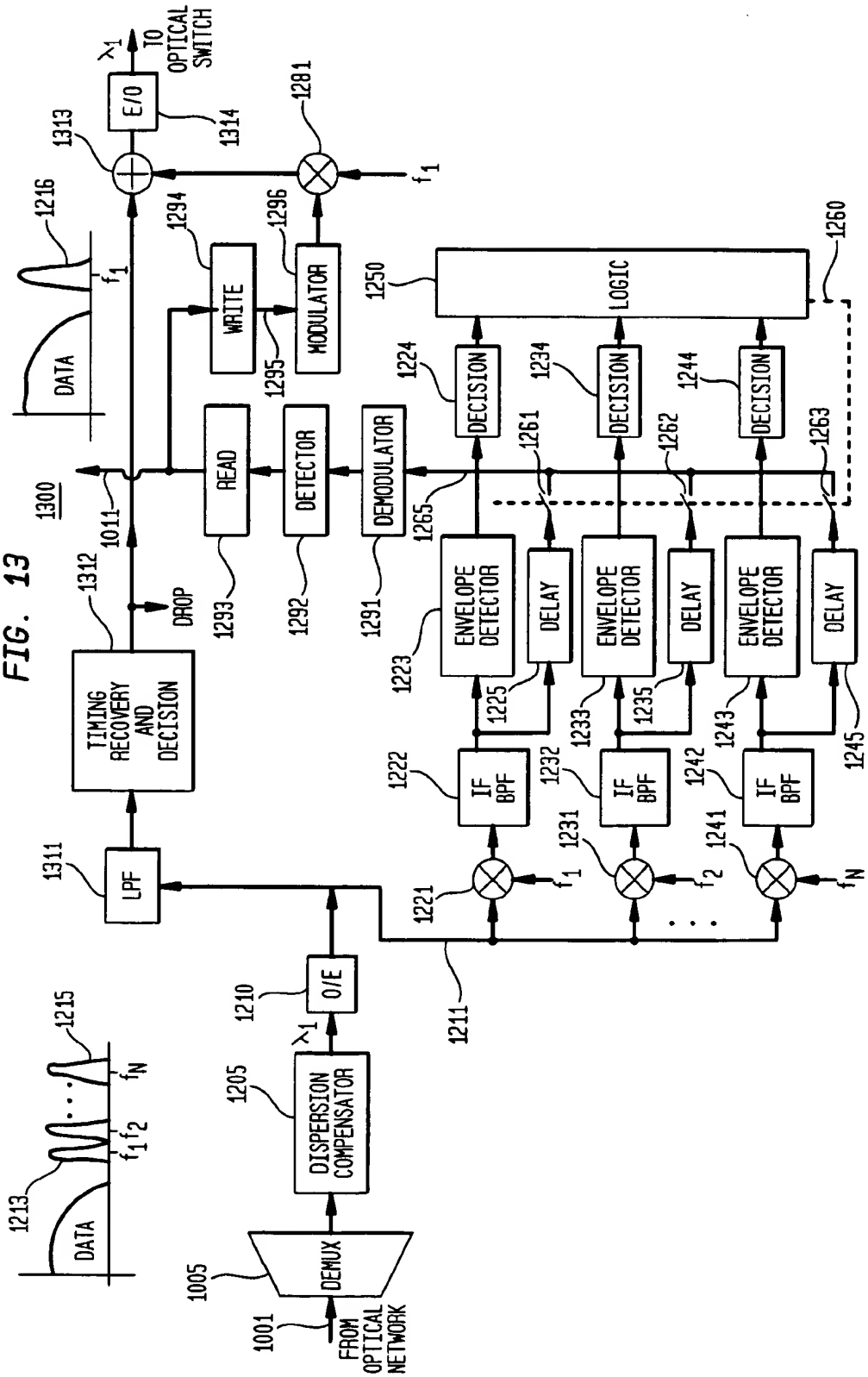


FIG. 13
1300
1001
FROM OPTICAL NETWORK
1005
DEMUX
1205
DISPERSION COMPENSATOR
1210
O/E
1211
1213
DATA
1215
1216
DATA
1221
1222
IF BPF
1223
ENVELOPE DETECTOR
1224
DECISION
1225
DELAY
1231
1232
IF BPF
1233
ENVELOPE DETECTOR
1234
DECISION
1235
DELAY
1241
1242
IF BPF
1243
ENVELOPE DETECTOR
1244
DECISION
1245
DELAY
1250
LOGIC
1260
1261
1262
1263
1265
1291
DEMODULATOR
1292
DETECTOR
1293
READ
1294
WRITE
1295
1296
MODULATOR
1311
LPF
1312
TIMING RECOVERY AND DECISION
1313
1314
E/O
TO OPTICAL SWITCH
1281
DROP
1011

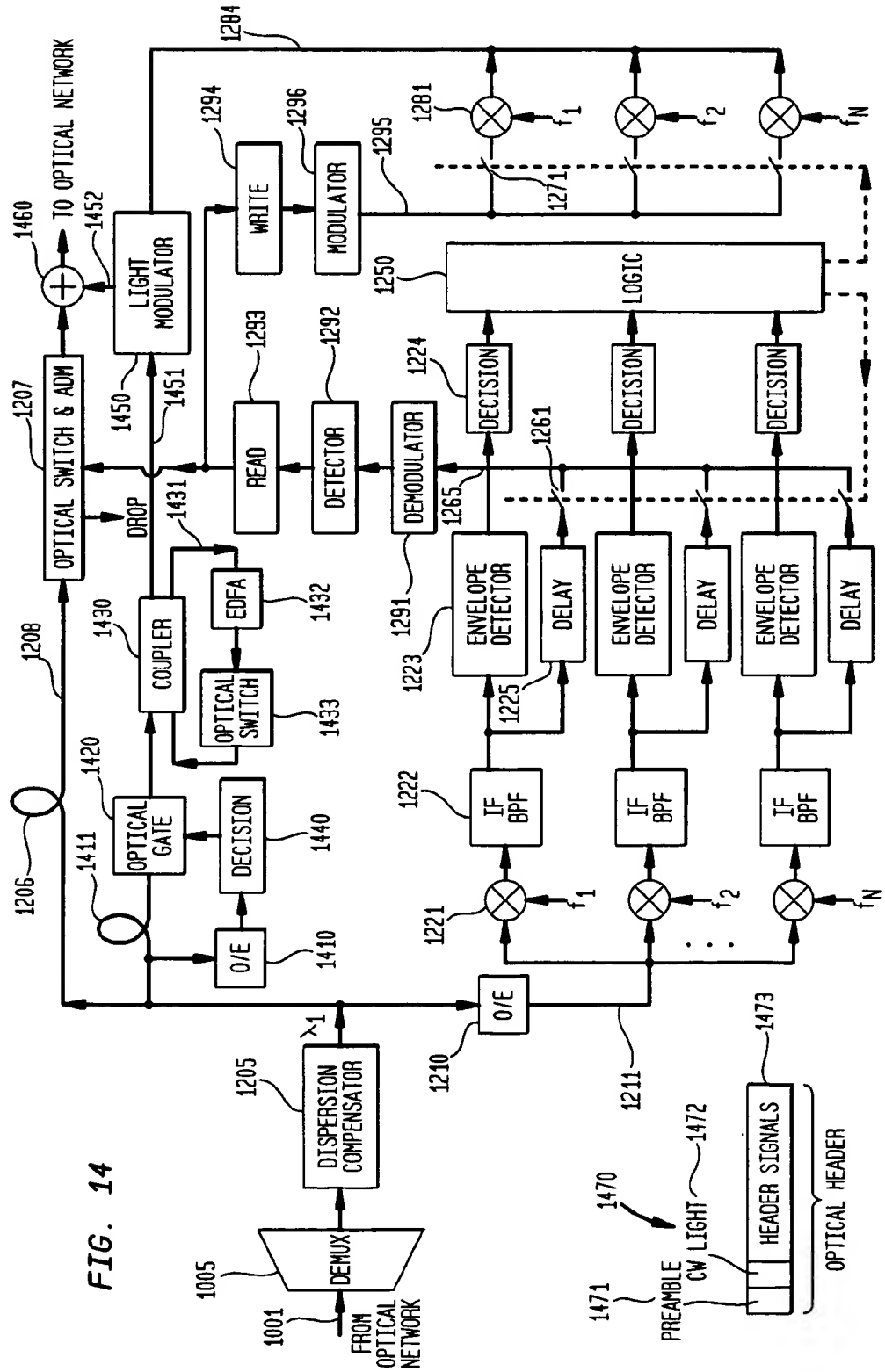
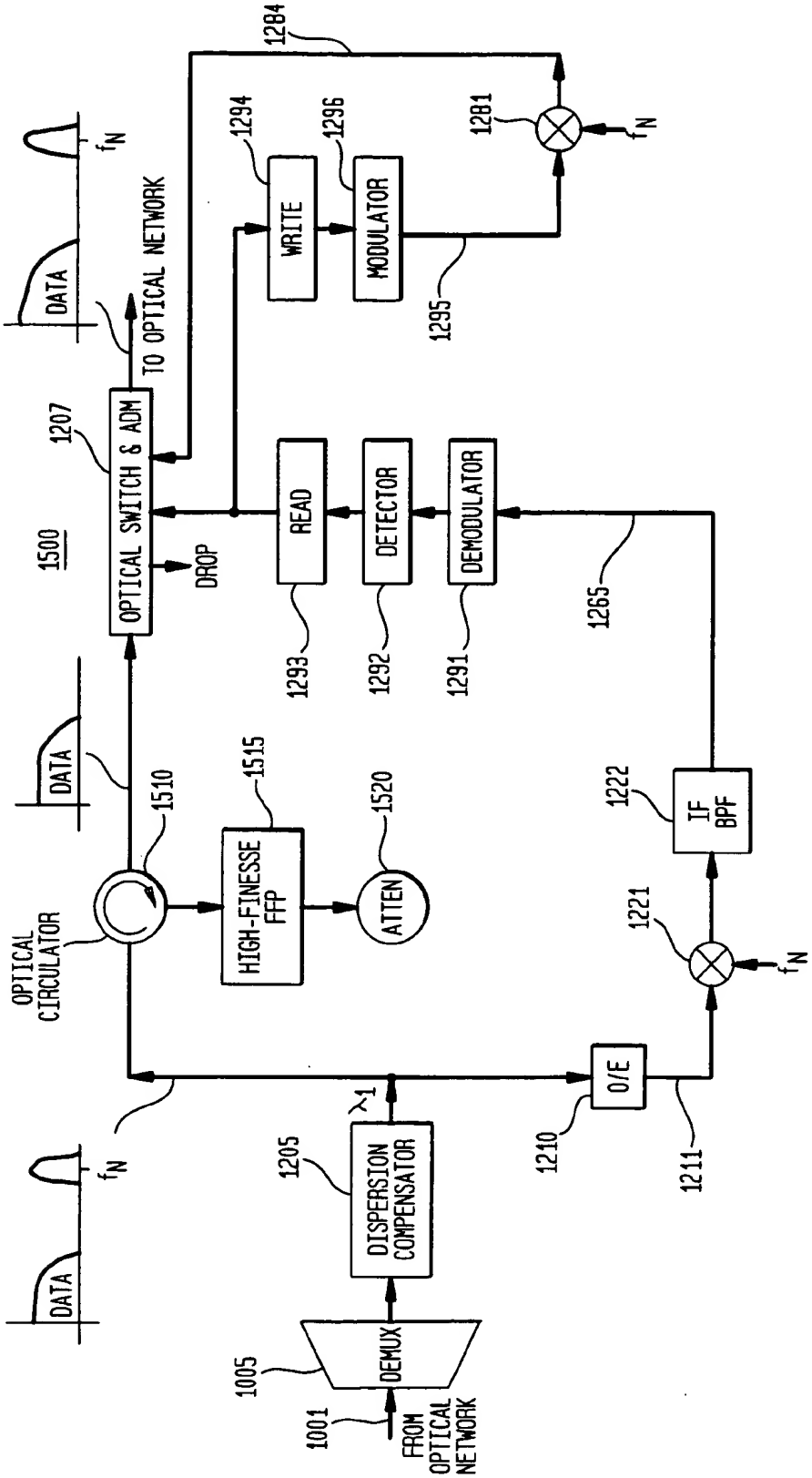

1284
TO OPTICAL NETWORK
1460
1452
LIGHT MODULATOR
WRITE
1294
1296
MODULATOR
1295
1281
f_1
f_2
f_N
1271
1250
LOGIC
1207
OPTICAL SWITCH & ADM
1450
1451
READ
1293
DETECTOR
1292
DEMODULATOR
1224
DECISION
1261
1265
DROP
1431
EDFA
1432
1430
COUPLER
OPTICAL SWITCH
1433
1208
1420
OPTICAL GATE
1411
DECISION
1440
1206
O/E
1410
1291
ENVELOPE DETECTOR
DELAY
1223
1225
1222
IF BPF
1221
f_1
f_2
f_N
O/E
1210
1211
$\lambda 1$
1205
DISPERSION COMPENSATOR
1005
DEMUX
1001
FROM OPTICAL NETWORK
1470
1472
CW LIGHT
1473
HEADER SIGNALS
OPTICAL HEADER
1471
PREAMBLE

FIG. 14

FIG. 15


1284
1294
1296
1281
f_N
DATA
f_N
WRITE
MODULATOR
TO OPTICAL NETWORK
1295
1207
OPTICAL SWITCH & ADM
1500
DROP
READ
DETECTOR
DEMODULATOR
1265
1293
1292
1291
DATA
1510
1515
1520
1222
IF BPF
HIGH-FINESSE FFP
ATTEN
OPTICAL CIRCULATOR
1221
f_N
O/E
λ_1
1205
DISPERSION COMPENSATOR
1210
1211
f_N
DATA
1005
DEMUX
1001
FROM OPTICAL NETWORK

HIGH-THROUGHPUT, LOW-LATENCY NEXT GENERATION INTERNET NETWORKS USING OPTICAL LABEL SWITCHING AND HIGH-SPEED OPTICAL HEADER GENERATION, DETECTION AND REINSERTION

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of application Ser. No. 09/118,437 filed Jul. 17, 1998, now U.S. Pat. No. 6,111,673 , as well as a non-provisional application of provisional application Serial No. 60/104,443 filed Oct. 16, 1998.

BACKGROUND OF THE DISCLOSURE

1 . Field of the Invention

This invention relates to optical communication systems and, more particularly, to an optical system which accommodates network traffic with high throughput and low latency and effects high-speed header detection and generation.

2 . Description of the Background Art

Recent research advances in optical Wavelength Division Multiplexing (WDM) technology have fostered the development of networks that are orders of magnitude higher in transmission bandwidth than existing commercial networks. While such an increase in throughput is impressive on its own, a corresponding decrease in network latency must also be achieved in order to realize the Next Generation Internet (NGI) vision of providing the next generation of ultra high speed networks that can meet the requirements for supporting new applications, including national initiatives. Towards this end, current research efforts have focused on developing an ultra-low latency Internet Protocol (IP) over WDM optical packet switching technology that promises to deliver the two-fold goal of both high throughput with low latency. Such efforts, while promising, have yet to fully realize this two-fold goal.

There are a number of challenging requirements in realizing such IP/WDM networks. First, the NGI network must inter-operate with the existing Internet and avoid protocol conflicts. Second, the NGI network must provide not only ultra low-latency, but must take advantage of both packet-switched (that is, bursty) IP traffic and circuit-switched WDM networks. Third, it is advantageous if the NGI network does not depend upon precise synchronization between signaling and data payload. Finally, a desired objective is that the NGI network accommodates data traffic of various protocols and formats so that it is possible to transmit and receive IP as well as non-IP signals without the need for complicated synchronization or format conversion.

Comparison with Other Work

The Multi-Wavelength-Optical Network (MONET) system, as reported in the article "MONET: Multi-Wavelength Optical Networking" by R. E. Wagner, et al. and published in the Journal of Lightwave Technology, Vol. 14, No. 6, June 1996, demonstrated a number of key milestones in optical network including transparent transmission of multi-wavelength through more than 12 reconfigurable network elements spread over the national scale fiber distance. The network, however, is circuit-switched and suffers inefficiency in accommodating bursty traffic. The typical connection setup time from request to switching is a few seconds, limited by capabilities of both Network Control & Management (NC&M) and hardware. Recent efforts within the MONET program to improve on the efficiency concentrated on the "Just-in-Time signaling" scheme. This method utilizes embedded 1510 nm NC&M signaling which precedes the data payload by an estimated delay time. This estimation must be accurately made for each network configuration for every wavelength in order to synchronize the signaling header and switching of the payload.

In accordance with the present invention, the optical packet header is carried over the same wavelength as the packet payload data. This approach mitigates the issue of header and payload synchronization. Furthermore, with a suitable use of optical delay at each intermediate optical switch, it eliminates the need to estimate the initial burst delay by incorporating the optical delay directly at the local switches. This makes a striking difference with Just-In-Time signaling in which the delay at each switch along the path needs to be known ahead of time and must be entered in the calculation for the total delay. Lastly, there is little time wasted in requesting a connection time and actually achieving a connection. In comparison to a few second delays seen in MONET, the present inventive subject matter reduces the delay to minimal, only limited by the actual hardware switching delays at each switch. The current switching technology realizes delays of only several microseconds, and shorter delays will be possible in the future. Such a short delay can be incorporated by using an optical fiber delay line at each network element utilizing switches. The present inventive subject matter achieves the lowest possible latency down to the fundamental limit of the hardware, and no lower latency can be achieved by any other technique.

The Optical Networks Technology Consortium (ONTC) results were reported in the article "Multiwavelength Reconfigurable WDM/ATM/SONET Network Testbed" by Chang et al. and published in the Journal of Lightwave Technology, Vol. 14, No. 6, June 1996. Both Phase I (155 Mb/s, 4-wavelength) and Phase II (2.5 Gb/s, 8-wavelength) of the ONTC program were configured on a Multihop ATM-based network. While such an ATM based architecture added a large overhead and excluded the possibility of a single-hop network, the packet/header signaling was made possible by utilizing the isochronous ATM cell itself This communication of NC&M information is made through the same optical wavelength, potentially offering similar benefits as with the technique of the present invention. However, the inventive technique offers a number of significant advantages over the ATM-based signaling. First, the inventive technique offers a single hop connection for the payload without the need to convert to electrical signals and buffer the packets. Second, it offers far more efficient utilization of the bandwidth by eliminating excessive overheads. Third, it allows strictly transparent and ultra-low latency connections.

The DARPA sponsored All-Optical-Network (AON) Consortium results were reported in an article entitled "A Wideband All-Optical WDM Network", by I. P. Kaminow et al. and published in the IEEE Journal on Selected Areas of Communication, Vol. 14, No. 5, June, 1996. There were actually two parts of the AON program: WDM as reported in the aforementioned article, and TDM reported in a companion paper in the same issue. First the WDM part of the AON program is first discussed, followed by the TDM part.

The AON architecture is a three-level hierarchy of subnetworks, and resembles that of LANs, MANs, and WANs seen in computer networks. The AON provides three basic services between Optical Terminals (OTs): A, B, and C services. A is a transparent circuit-switched service, B is a transparent time-scheduled TDM/WDM service, and C is

a non-transparent datagram service used for signaling. The B service uses a structure where a 250 microsecond frame is used with 128 slots per frame. Within a slot or group of slots, a user is free to choose the modulation rate and format. The B-service implemented on the AON architecture is closest to the IP over WDM which is the subject matter of the present invention. However, the separation of NC&M signaling in the C-service with the payload in the B-service requires careful synchronization between the signaling header and the payload. This requirement becomes far more stringent as the 250 microsecond frame is used with 128 slots per frame with arbitrary bit rates. Not only the synchronization has to occur at the bit level, but this synchronization has to be achieve across the entire network. The scalability and interoperability are extremely difficult since these do not go in steps with the network synchronization requirement. The present inventive subject matter requires only that the payload and the header are transmitted and received simultaneously, inter-operates with existing IP and non-IP traffic, and offers scalability.

TDM efforts are aimed at 100 Gb/s bit rates. In principle, such ultrafast TDM networks have the potential to provide truly flexible bandwidth on demand at burst rates of 100 Gb/s. However, there are significant technological challenges behind such high bit rate systems mainly related to nonlinearities, dispersion, and polarization degradations in the fiber. While the soliton technologies can alleviate some of the difficulties, it still requires extremely accurate synchronization of the network—down to a few picoseconds. In addition, the header and the payload must have the identical bit rates, and as a consequence, bit-rate transparent services are difficult to provide. The subject matter in accordance with the present invention does not depend on precise synchronization, relies on no 100 Gb/s technologies, and offers transparent services.

The Cisco Corporation recently announced a product based on Tag-Switching and the general description of Cisco's Tag-Switching is available at the world-wide-web site, (http://www.cisco.com/warp/public/732/tag/). Cisco's (electronic) Tag Switching assigns a label or "tag" to packets traversing a network of routers and switches. In a conventional router network, each packet must be processed by each router to determine the next hop of the packet toward its final destination. In an (electronic) Tag Switching network, tags are assigned to destination networks or hosts. Packets then are switched through the network with each node simply swaps tags rather than processing each packet. An (electronic) Tag Switching network will consist of a core of (electronic) tag switches (either conventional routers or switches), which connect to (electronic) tag edge routers on the network's periphery. (Electronic) Tag edge routers and tag switches use standard routing protocols to identify routes through the network. These systems then use the tables generated by the routing protocols to assign and distribute tag information via a Tag Distribution Protocol. Tag switches and tag edge routers receive the Tag Distribution Protocol information and build a forwarding database. The database maps particular destinations to the tags associated with those destinations and the ports through which they are reachable.

When a tag edge router receives a packet for forwarding across the tag network, it analyzes the network-layer header and performs applicable network layer services. It then selects a route for the packet from its routing tables, applies a tag and forwards the packet to the next-hop tag switch.

The tag switch receives the tagged packet and switches the packet based solely on the tag, without re-analyzing the network-layer header. The packet reaches the tag edge router at the egress point of the network, where the tag is stripped off and the packet delivered. After Cisco made its announcement about (Electronic) Tag Switching, the IETF (Internet Engineering Task Force) has recommended a MPLS (Multiprotocol Label Switching) to implement standardized, vendor-neutral (electronic) tag-switching function in routers and switches, including ATM switches.

A number of features in the Cisco's (electronic) Tag Switching is similar to the Optical Tag Switching which is the subject matter of the present invention, with the features aimed at the similar goals of simplifying the processing required for packet routing. The key differences are as follows. First, the optical tag switching is purely optical in the sense that both tag and data payload are in an optical form. While each plug-and-play module (a component of the present inventive system) senses the optical tag, the actual packet does not undergo optical-to-electrical conversion until it comes out of the network The Cisco's (electronic) Tag Switching will be all electrical, and applies electronic detection, processing, and retransmission to each packet at each router. Secondly, the Optical Tag Switching of the present invention achieves lowest possible latency and does not rely on utilizing buffers. Electronic tag switching will have far greater latency due to electronic processing and electronic buffering. Thirdly, the Optical Tag Switching of the present invention utilizes path deflection and/or wavelength conversion to resolve blocking due to contention of the packets, whereas the Electronic Tag Switching will only utilize electronic buffering as a means to achieve contention resolution at the cost of increased latency, and the performance is strongly dependent on packet size. The present invention covers packets of any length. Lastly, the Optical Tag Switching of the present invention achieves a strictly transparent network in which data of any format and protocol can be routed so long as it has a proper optical tag. Hence the data can be digital of any bit rate and modulation formats. The Electronic Tag Switching requires that data payload to have the given digital bit rate identical to the electronic tag since the routers must buffer them electronically.

Another representative technology that serves as background to the present invention is the so-called Session Deflection Virtual Circuit Protocol (SDVC), which is based on deflection routing method. The paper entitled "The Manhattan Street Network", by N. F. Maxemchuk" as published in the Proceedings on IEEE Globecom '85, pp 255–261, December 1985, discusses that when two packets attempt to go to the same destination, one packet can be randomly chosen for the preferred output link and the other packet is "deflected" to the non-preferred link. This means that packets will occasionally take paths that are not shortest paths. The deflection method utilized by the present invention does not 'randomly' select the packet to go to the most preferred path; rather, it attempts to look into the priorities of the packets, and send the higher priority packet to be routed to the preferred path. The packets will be deflected if they have lower priorities; however, both 'path deflection' and 'wavelength deflection' are utilized. The path deflection is similar to conventional SDVC in that the optical packet will be simply routed to the path of the next preference at the same wavelength. The wavelength deflection allows the optical packet to be routed to the most preferred path but at a different wavelength. This wavelength deflection is achieved by wavelength conversion at the network elements. Partially limited wavelength conversion is utilized, meaning not all wavelengths will be available as destination wave-

lengths for a given originating wavelength. The wavelength deflection allows resolution of blocking due to wavelength contentions without increasing the path delay. The combination of path and wavelength deflections offers sufficiently large additional connectivities for resolving packet contentions; however, the degree of partial wavelength conversion can be increased when the blocking rate starts to rise. Such scalability and flexibility of the network is not addressed by conventional SDVC.

Besides the foregoing overall system considerations elucidated above, there is also the issue of how to effectively detect and/or re-insert a header which is combined with a data payload for propagation over the network using the same optical wavelength. The primary focus in the literature has been on a technique for combining sub-carrier headers with a baseband data payload. The very first two articles addressing this issued were published in 1992 by A. Bidman et. al., who combined a 2.56 Gb/s data payload with a 40 Mb/s header on 3 GHz carrier [A. Budman, E. Eichen, J. Schalafer, R. Olshansky, and F. McAleavey, "Multigigabit optical packet switch for self-routing networks with subcarrier addressing," Techical Digest, paper TuO4, pp.90–91, OFC'92], and W. I. Way et al., who combined a 2.488 Gb/s data payload with a tunable microwave pilot tone (tuned between 2.520 and 2.690 GHz) to route SONET packet in a WDM ring network via acousto-optical tunable filter [W. I. Way, D. A. Smith, J. J. Johnson, H. Izadpanah, and H. Johnson, "Self-routing WDM high-capacity SONET ring network," Technical Digest, paper TuO2, pp.86–87, OFC'92, and W. I. Way, D. A. Smith, J. J. Johnson, and H. Izadpanah, "A self-routing WDM high-capacity SONET ring network," IEEE Photonics Technology Letters, vol.4, pp.402–404, April 1992.2,3]. Both of articles used a single laser diode to carry the data payload and sub-carrier header. This technique has also been extensively studied in a local-area DWDM optical packet-switched network [R. T. Hofineister, L. G. Katzovsky, C. L. Lu, P. Poggiolini, and F. Yang, "CORD: optical packet-switched network testbed," Fiber and Integrated Optics, vol. 16, pp. 199–219, 1997], and several other all-optical networks [E. Park and A. E. Willner, "Network demonstration of self-routing wavelength packets using an all-optical wavelength shifter and QPSK subcarrier routing control," IEEE Photonics Technology Letters, vol.8, pp.938–940, 1996; and M. Shell, M. Vaughn, A. Wang, D. J. Blumenthal, P. J. Rigole, and S. Nilsson, "Experimental demonstration of an all-optical routing node for multihop wavelength routed networks," IEEE Photonic Technology Letters, vol.8, pp.1391–1393, 1996].

Instead of combing a sub-carrier headers with the data payload in the electrical domain, they have also been combined in the optical domain by using two laser diodes at different wavelengths [B. H. Wang, K. Y. Yen, and W. I. Way, "Demonstration of gigabit WDMA networks using parallel-processed sub-carrier hopping pilot-tone (P^3) signaling technique," IEEE Photonics Technology Letters, vol.8, pp.933–934, July 1996].

However, using two wavelengths to transport data payload and header separately may not be practical in the following sense: in an all-optical DWDM network, it is preferred that the header, which may contain network operations information, travels along the same routes as data payload so that it can truthfully report the updated status of the data payload. If the header and the data payload were carried by different wavelengths, they could be routed in the network with entirely different paths, and the header may not report what the data payload has really experienced. Therefore, although it is preferred that the sub-carrier header and the data payload be carried by the same wavelength, the art is devoid of such teachings and suggestions.

The sub-carrier pilot-tone concept presented in Wang et al. was extended to multiple pilot tones by Shieh et al. [W. Shieh and A. E. Willner, "A wavelength routing node using multifunctional semiconductor optical amplifiers and multiple-pilot-tone-coded subcarrier control headers," IEEE Photonics Technology Letters, vol.9, pp. 1268–1270, September 1997.], mainly for the purpose of increasing the number of network addresses.

Recently, consideration has been given to 'header replacement' for the high-throughput operation in a packet-switched network in which data paths change due to link outages, output-port contention, and variable traffic patterns. Moreover, header replacement could be useful for maintaining protocol compatibility at gateways between different networks. However, the only method which has been reported is for time-division-multiplexed header and data payload requires an extremely high accuracy of timing synchronization among network nodes [X. Jiang, X. P. Chen, and A. E. Willner, "All optical wavelength independent packet header replacement using a long CW region generated directly from the packet flag," IEEE Photonics Technology Letters, vol.9, pp.1638–1640, November 1998].

From this overview of the art pertaining to details of header generation and detection, it is readily understood that the art is devoid of teachings and suggestions wherein sub-carrier multiplexed packet data payload and multiple sub-carrier headers (including old and new ones) are deployed so that a >2.5 Gbps IP packet can be routed through a national all-optical DWDM network by the (successive) guidance of these sub-carrier headers, with the total number of sub-carrier headers that can be written is in the range of forty or more.

SUMMARY OF THE INVENTION

The present invention utilizes a unique optical signaling header technique applicable to optical networks. Packet routing information is embedded in the same channel or wavelength as the data payload so that both the header and data information propagate through the network with the same path and the associated delays. However, the header routing information has sufficiently different characteristics from the data payload so that the signaling header can be detected without being affected by the data payload and that the signaling header can also be stripped off without affecting the data payload. The inventive subject matter allows such a unique signal routing method to be overlaid onto the conventional network elements in a modular manner, including the insertion, detection and processing of the optical header.

In accordance with a broad method aspect of the present invention commensurate with the overall NGI system, a method for propagating a data payload from an input network element to an output network element in a wavelength division multiplexing system composed of a plurality of network elements, given that the data payload has a given format and protocol, includes the following steps: (a) adding a header to the data payload prior to inputting the data payload to the input network element, the header having a format and protocol and being indicative of the local route through each of the network elements for the data payload and the header, the format and protocol of the data payload being independent of the format and protocol of the header; and (b) detecting the header at each of the network elements as the data payload and header propagate through the WDM network, wherein the header is composed of one or more

header signals each being conveyed by a distinct sub-carrier frequency and arranged so that the highest detectable sub-carrier frequency corresponds to an active header signal, the plurality of sub-carrier frequencies occupying a frequency band above the data payload, such that the step of detecting includes the steps of (i) concurrently measuring the header signals to produce a header selection signal, (ii) selecting the active header signal as conveyed by the highest detectable sub-carrier frequency under control of the header selection signal, and (iii) processing the active header signal to produce a switch control signal to route the header and the data payload through the network element.

In accordance a broad system aspect of the present invention for an individual network element, a system for detecting a header propagating with an data payload at a given optical wavelength, the header being composed of one or more header signals each being conveyed by a distinct sub-carrier frequency and arranged so that the highest detectable sub-carrier frequency corresponds to an active header signal, the plurality of sub-carrier frequencies occupying a frequency band above the data payload, includes the following components: (a) a measurement device for concurrently measuring the header signals to produce a header selection signal; (b) a selector, coupled to the measurement device, for determining the active header signal as conveyed by the highest detectable sub-carrier frequency under control of the header selection signal; and (c) a processor, coupled to the selector, for processing the active header signal to produce a switch control signal to route the header and the data payload.

BRIEF DESCRIPTION OF THE DRAWINGS

The teachings of the present invention can be readily understood by considering the following detailed description in conjunction with the accompanying drawings, in which:

FIG. **1** is a pictorial representation of a general network illustrating the coupling between the optical and electrical layers of the network;

FIG. **2** illustrates the optical layer of the network of FIG. **1** showing the relationship between the optical signal header and data payload, and the use of the header/payload in network setup;

FIG. **3** is a high-level block diagram an optical transmitter in accordance with the present invention for header encoding;

FIG. **4** is a high-level block diagram an optical receiver in accordance with the present invention for header decoding;

FIG. **5** is illustrative of a WDM circuit-switched backbone network;

FIG. **6** illustrates a network element of FIG. **1** with its embedded switch and the use of local routing tables;

FIG. **7** depicts a block diagram of an illustrative embodiment of a header encoder circuit for the Plug-&-Play module of FIG. **3**;

FIG. **8** depicts a block diagram of an illustrative embodiment of a header remover circuit for the Plug-&-Play module of FIG. **3**;

FIG. **9** depicts a block diagram of an illustrative embodiment of a header detector circuit for the Plug-&-Play module of FIG. **4**;

FIG. **10** depicts a block diagram for a more detailed embodiment of FIG. **4** wherein the label-switch controller includes interposed demultiplexers, and header detectors and fast memory;

FIG. **11** is a flow diagram for the processing effected by each label-switch controller of FIG. **10**;

FIG. **12** is a block diagram of circuitry for detecting the active header signal and for inserting a new active header signal without local injection of light;

FIG. **13** is a block diagram of re-set circuitry for deleting all incoming header signals, and for inserting a new original header signal;

FIG. **14** is a block diagram of circuitry for detecting the active header signal and for inserting a new active header signal using the local injection of light; and

FIG. **15** is a block diagram of circuitry for removing a single header signal and replacing the removed header signal with a new header signal.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

DETAILED DESCRIPTION

In order to gain an insight into the fundamental principles in accordance with the present invention as well as to introduce terminology useful in the sequel, an overview is first presented, followed by an elucidation of an illustrative embodiment.

Overview

The present invention relates to a network for realizing low latency, high throughput, and cost-effective bandwidth-on-demand for large blocks of data for NGI applications. Cost-effective and interoperable upgrades to the network are realized by interposing portable 'Plug-and-Play' modules on the existing WDM network elements to effect so-called "WDM optical label switching" or, synonymously, "optical label switching". The invention impacts primarily the hardware for the NGI network from the network element design perspective.

As alluded to, the methodology carried out by the network and concomitant circuitry for implementing the network are engendered by a technique called WDM optical label-switching—defined as the dynamic generation of a routing path for a burst duration by an in-band optical signaling header. Data packets are routed through the WDM network using an in-band WDM signaling header for each packet. At a switching node, the signaling header is processed and the header and the data payload (1) may be immediately forwarded through an already existing flow state connection, or (2) a path can be setup for a burst duration to handle the header and the data payload. WDM label-switching enables highly efficient routing and throughput, and reduces the number of IP-level hops required by keeping the packets routing at the optical level to one hop as managed by the Network Control and Management (NC&M) which creates and maintains routing information.

The depiction of FIG. **1** shows the inter-relation between optical layer **120** and electrical layer **110** of generic network **100** as provided by intermediate layer **130** coupling the optical layer and the electrical layer. Electrical layer **110** is shown, for simplicity, as being composed of two conventional IP routers **111** and **112**. Optical layer **120** is shown as being composed of network elements or nodes **121–125**. Intermediate layer **130** depicts conventional ATM/SONET system **131** coupling IP router **112** to network element **122**. Also shown as part of layer **130** is header network **132**, which in accordance with the present invention, couples IP router **111** to network element **121**. FIG. **1** pictorially

illustrates the location of network **132** on a national-scale, transparent WDM-based backbone network with full interoperability and reconfigurability. It is important to emphasize at this point that the elements of FIG. **1** are illustrative of one embodiment in accordance with the present invention; thus, for example, element **111** may, in another embodiment, be an ATM router or even a switch.

Now with reference to FIG. **2**, optical layer **120** of FIG. **1** is shown in more detail including the basic technique, in accordance with the present invention, for setting up a fast connection in optical network **201**, composed of network elements **121–125**; the setup uses optical signaling header **210** for the accompanying data payload **211**. This technique combines the advantages of circuit-switched based WDM and packet-switched based IP technologies. New signaling information is added in the form of an optical signal header **210** which is carried in-band within each wavelength in the multi-wave-length transport environment. Optical signaling header **210** is a label containing routing and control information such as the source, destination, priority, and the length of the packet, propagates through optical network **201** preceding data payload **211**. Each WDM network element **121–125** senses optical signaling header **210**, looks-up a connection table (discussed later), and takes necessary steps such as cross-connections, add, drop, or drop-and-continue. The connection table is constantly updated by continuous communication between NC&M **220** and WDM network elements **121–125**. Data payload **211**, which follows optical signaling header **210**, is routed through a path in each network element (discussed later) as established by the connection. With the arrangement of FIG. **2**, there is no need to manage the time delay between optical signaling header **210** and data payload **211**, shown by T in FIG. **2**, because each network element provides the optical delay needed for the short time required for connection set-up within each network element via delay on an interposed fiber. Moreover, the format and protocol of the data payload is independent of that of the header, that is, for a given network whereas the format and protocol of the header are pre-determined, the format and the protocol of the data payload can be the same as or different from those of the header.

Each destination is associated with a preferred path which would minimize 'the cost'—in FIG. **2**, the overall path from source **123** to destination **122** includes paths **201** and **202** in cascade, both utilizing wavelength WP. This cost is computed based on the total propagation distance, the number of hops, and the traffic load. The preferred wavelength is defaulted to the original wavelength. For example, the preferred wavelength on path **202** is WP. If this preferred path at the default wavelength is already occupied by another packet, then network element **121** quickly decides if there is an available alternate wavelength WA through the same preferred path. This alternate wavelength must be one of the choices offered by the limited wavelength conversion in network element **121**. If there is no choice of wavelengths which allows transport of the packet through the most preferred path, the next preferred path is selected (path deflection). For example, in FIG. **2**, paths **203** and **204** in cascade may represent the alternative path. At this point, the preferred wavelength will default back to the original wavelength WP. The identical process of looking for an alternate wavelength can proceed if this default wavelength is again already occupied. In FIG. **2**, path **203** is an alternative path with the same wavelength WP, and path **204** is an alternate path using alternate wavelength WA. In an unlikely case where there is no combination of path and wavelength deflection can offer transport of the packet, network element **121** will decide to drop the packet of lower priority. In other words, the new packet transport through the preferred path at the originating wavelength takes place by dropping the other packet of the lower priority which is already occupying the preferred path.

Network elements **121–125** are augmented with two types of so-called 'Plug-and-Play' modules to efficiently handle bursty traffic by providing packet switching capabilities to conventional circuit-switched WDM network elements **121–125** whereby signaling headers are encoded onto IP packets and are removed when necessary.

The first type of 'Plug-and-Play' module, represented by electro-optical element **132** of FIG. **1**, is now shown in block diagram form in FIG. **3**. Whereas conceptually module **132** is a stand-alone element, in practice, module **132** is integrated with network element **121** as is shown in FIG. **3**; module **132** is interposed between compliant client interface (CCI) **310** of network element **121** and IP router **111** to encode optical signaling header **210** onto the packets added into the network via header encoder **321**, and to remove optical signaling header **210** from the packets dropping out of the network via header remover **322**.

Generally, encoding/removing module **132** is placed where the IP traffic is interfaced into and out of the WDM network, which is between the client interface of the network element and the IP routers. The client interfaces can be either a CCI-type or a non-compliant client interfaces (NCI)-type. At these interfaces, header encoder **321** puts optical header **210** carrying the destination and other information in front of data payload **211** as the IP signal is transported into network **201**. Optical header **210** is encoded in the optical domain by an optical modulator (discussed later). Signaling header remover **322** deletes header **210** from the optical signal dropped via a client interface, and provides an electrical IP packet to IP router **111**.

More specifically, module **132** accepts the electrical signal from IP router **111**, converts the electrical signal to a desired compliant wavelength optical signal, and places optical header **210** in front of the entire packet. Module **132** communicates with NC&M **220** and buffers the data before optically converting the data if requested by NC&M **220**. Module **132** employs an optical transmitter (discussed later) with the wavelength matched to the client interface wavelength. (As indicated later but instructive to mention here, module **132** is also compatible with NCI **404** of FIG. **4** since the wavelength adaptation occurs in the NCI; however, the bit-rate-compatibility of NCI wavelength adaption and the IP signal with optical headers must be established in advance.)

FIG. **4** depicts a second type of 'Plug-and-Play' module, optical element **410**, which is associated with each WDM network element **121–125**, say element **121** for discussion purposes. Module **410** is interposed between conventional network element circuit switch controller **420** and conventional switching device **430**. Module **410** detects information from each signaling header **210** propagating over any fiber **401–403**, as provided to module **410** by tapped fiber paths **404–406**. Module **410** functions to achieve very rapid table look-up and fast signaling to switching device **430**. Switch controller **420** is functionally equivalent to the conventional "craft interface" used for controlling the network elements; however, in this case, the purpose of this switch controller **420** is to accept the circuit-switched signaling from NC&M **220** and determine which control commands are to be sent to label switch controller **410** based on the priority. Thus, label switch controller **410** receives

circuit-switched control signals from network element circuit switch controller **420**, as well as information as derived from each signaling each header **210**, and intelligently chooses between the circuit-switched and the label-switched control schemes. The switches (discussed later) comprising switching device **430** also achieve rapid switching. The delay imposed by fibers **415**, **416**, or **416**, which are placed in input paths **401–403** to switching device **430**, are such that the delay is larger than the total time it takes to read signaling header **210**, to complete a table look-up, and to effect switching. Approximately, a 2 km fiber provides 10 microsecond processing time. The types of WDM network elements represented by elements **121–125** and which encompass switching device **430** include: Wavelength Add-Drop Multiplexers (WADMs); Wavelength Selective Cross-connects (WSXCs); and Wavelength Interchanging Cross-connects (WIXCs) with limited wavelength conversion capabilities.

In operation, module **410** taps a small fraction of the optical signals appearing on paths **401–403** in order to detect information in each signaling header **210**, and determine the appropriate commands for switching device **430** after looking up the connection table stored in module **410**. The fiber delay is placed in paths **401–403** so that the packet having header **210** and payload **211** reaches switching device **430** only after the actual switching occurs. This fiber delay is specific to the delay associated with header detection, table look-up, and switching, and can typically be accomplished in about 10 microseconds with about 2 km fiber delay in fibers **415–417**.

Packets are routed through network **201** using the information in signaling header **210** of each packet. When a packet arrives at a network element, signaling header **210** is read and either the packet (a) is routed to a new appropriate outbound port chosen according to the label routing look-up table, or (b) is immediately forwarded through an already existing label-switching originated connection within the network element. The latter case is referred to as "flow switching" and is supported as part of optical label-switching; flow switching is used for large volume bursty mode traffic.

Label-switched routing look-up tables are included in network elements **121–125** in order to rapidly route the optical packet through the network element whenever a flow switching state is not set-up. The connection set-up request conveyed by optical signaling header **210** is rapidly compared against the label-switch routing lookup table within each network element. In some cases, the optimal connections for the most efficient signal routing may already be occupied. The possible connection look up table is also configured to already provide an alternate wavelength assignment or an alternate path to route the signal. Providing a limited number of (at least one) alternative wavelength significantly reduces the blocking probability. The alternative wavelength routing also achieves the same propagation delay and number of hops as the optimal case, and eliminates the difficulties in sequencing multiple packets. The alternate path routing can potentially increase the delay and the number of hops, and the signal-to noise-ratio of the packets are optically monitored to eliminate any possibility of packets being routed through a large number of hops. In the case where a second path or wavelength is not available, contention at an outbound link can be settled on a first-come, first-serve basis or on a priority basis. The information is presented to a regular IP router and then is reviewed by higher layer protocols, using retransmission when necessary.

Routing Example

An illustrative WDM circuit-switched backbone network **500** for communicating packets among end-users in certain large cities in the United States is shown in pictorial form in FIG. **5**—network **500** is first discussed in terms of its conventional operation, that is, before the overlay of WDM optical label switching in accordance with the present invention is presented.

With reference to FIG. **5**, it is supposed that New York City is served by network element **501**, Chicago is served by network element **502**, . . . , Los Angeles is served by network element **504**, . . . , and Minneapolis by network element **507**. (Network elements may also be referred to as nodes in the sequel.) Moreover, NC&M **220** has logical connections (shown by dashed lines, such as channel **221** to network element **501** and channel **222** to network element **507**) to all network elements **501–507** via physical layer optical supervisory channels; there is continuous communication among NC&M **220** and network elements **501–507**. NC&M **220** periodically requests and receives information about: (a) the general state of each network element (e.g., whether it is operational or shut down for an emergency); (b) the optical wavelengths provided by each network element (e.g., network element **501** is shown as being served by optical fiber medium **531** having wavelength W1 and optical fiber medium **532** having wavelength W2 which connect to network elements **502** (Chicago) and **505** (Boston), respectively); and (c) the ports which are served by the wavelengths (e.g., port **510** of element **501** is associated with an incoming client interface conveying packet **520**, port **511** is associated with W1 and port **512** is associated with W2, whereas port **513** of element **502** is associated with W1).

Thus, NC&M **220** has stored at any instant the global information necessary to formulate routes to carry the incoming packet traffic by the network elements. Accordingly, periodically NC&M **220** determines the routing information in the form of, for example, global routing tables, and downloads the global routing tables to each of the elements using supervisory channels **221**, **222**, ... The global routing tables configure the ports of the network elements to create certain communication links. For example, NC&M **220** may determine, based upon traffic demand and statistics, that a fiber optic link from New York City to Los Angeles (network elements **501** and **504**, respectively) is presently required, and the link will be composed, in series, of W1 coupling port **511** of element **501** to port **513** in network element **502**; W1 coupling port **514** of element **502** to port **515** of element **503**; and W2 coupling port **516** of element **503** to port **517** of element **504**. Then, input packet **520** incoming to network element **501** (New York City) and having a destination of network element **504** (Los Angeles) is immediately routed over this established link. At network element **504**, the propagated packet is delivered as output packet **521** via client interface port **518**.

In a similar manner, a dedicated path between elements **506** and **507** (St. Louis and Minneapolis, respectively) is shown as established using W2 between network elements **506** and **502**, and W3 between elements **502** and **507**.

Links generated in this manner—as based upon the global routing tables—are characterized by their rigidity, that is, it takes several seconds for NC&M **220** to determine the connections to establish the links, to download the connectivity information for the links, and establish the input and output ports for each network element. Each link has characteristics of a circuit-switched connection, that is, it is basically a permanent connection or a dedicated path or "pipe" for long intervals, and only NC&M **220** can tear down and re-establish a link in normal operation. The benefit of such a dedicated path is that traffic having an origin and a destination which maps into an already-established dedi-

cated path can be immediately routed without the need for any set-up. On the other hand, the dedicated path can be, and most often is, inefficient in the sense that the dedicated path may be only used a small percentage of the time (e.g., 20%–50% over the set-up period). Moreover, switching device **430** (see FIG. **4**) embedded in each network element which interconnects input and output ports has only a finite number of input/output ports. If the above scenario is changed so that link from St. Louis to Minneapolis is required and a port already assigned to the New York to Los Angeles link is to be used (e.g., port **514** of network element **502**), then there is a time delay until NC&M **220** can respond and alter the global routing tables accordingly.

Now the example is expanded so that the subject matter in accordance with the principles of the present invention is overlaid on the above description. First, a parameter called the "label-switched state" is introduced and its use in routing is discussed; then, in the next paragraph, the manner of generating the label-switch state is elucidated. The label-switch state engenders optical label switching.

NC&M **220** is further arranged so that it may assign the label-switch state to each packet incoming to a network element from a client interface—the label-switch state is appended by Plug & Play module **132** and, for the purposes of the present discussion, the label-switch state is commensurate with header **210** (see FIG. **2**). The label-switch state is computed by NC&M **220** and downloaded to each network element **501–507** in the form of a local routing table. With reference to FIG. **6**, there is shown network element **501** and its embedded switch **601** in pictorial form. Also shown is incoming optical fiber **602**, with delay loop **603**, carrying packet **620** composed of header **210** and payload **211**—payload **211** in this case is packet **520** from FIG. **5**. Fiber **6022** delivers a delayed version of packet **620** to network element **501**. Also, a portion of the light energy appearing on fiber **602** is tapped via fiber **6021** and inputted to optical module **410** which processes the incoming packet **620** to detect header **210**—header **210** for packet **620** is shown as being composed of the label-switch state '11101011000',identified by reference numeral **615**. Also shown in FIG. **6** is local look-up table **610**, being composed of two columns, namely, "label-switch state" (column **611**), and "Local Address" (column **612**). The particular label-switch state for packet **620** is cross-referenced in look-up table **610** to determine the routing of the incoming packet. In this case, the label-switch state for packet **620** is the entry in the fourth row of look-up table **610**. The local switch address corresponding to this label-switch state is "0111", which is interpreted as follows: the first two binary digits indicate the incoming port, and the second two binary digits indicate the output port. In this case, for the exemplary four-input, four-output switch, the incoming packet is to be routed from input port "01" to output port "11", so switch **601** is switched accordingly (as shown). After the delay provided by fiber delay **603**, the incoming packet on fiber **6022** is propagated onto fiber **604** via switch **601**.

The foregoing description of label-switch state indicates how it is used. The manner of generating the label-switch state is now considered. NC&M **220**, again on a periodic basis, compiles a set of local look-up tables for routing/switching the packet through each corresponding network element (such as table **610** for network element **501**), and each look-up table is then downloaded to the corresponding network element. The generation of each look-up table takes into account NC&M **220**'s global knowledge of the network **500**. For instance, if incoming packet **620** to network **501** is destined for network **504** (again, New York to Los Angeles), if port **510** is associated with incoming port "01" and serves fiber **602**, and if outgoing port **511** is associated with outgoing port "11" and serves fiber **604**, then NC&M **220** is able to generate the appropriate entry in look-up table **610** (namely, the fourth row) and download table **610** to network element **510**. Now, when packet **520** is processed by electro-optical module **132** so as to add header **210** to packet **520** to create augmented packet **620**, NC&M **220**'s knowledge of the downloaded local routing tables as well as the knowledge of the destination address embedded in packet **520** as obtained via module **132** enables NC&M **220** to instruct module **132** to add the appropriate label-switch state as header **210**—in this case '11101011000'.

It can be readily appreciated that processing a packet using the label-switch state parameter is bursty in nature, that is, after switch **601** is set-up to handle the incoming label-switch state, switch **601** may be returned to its state prior to processing the flow state. For example, switch **601** may have interconnected input port '01'to output port '10'prior to the arrival of packet **620**, and it may be returned to the '0110'state after processing (as determined, for example, by a packet trailer). Of course, it may be that the circuit-switched path is identical to the label-switch state path, in which case there is no need to even modify the local route through switch **601** for processing the label-switch state. However, if it is necessary to temporarily alter switch **601**, the underlying circuit-switched traffic, if any, can be re-routed or re-sent.

As discussed so far, label switching allows destination oriented routing of packets without a need for the network elements to examine the entire data packets. New signaling information—the label—is added in the form of optical signal header **210** which is carried in-band within each wavelength in the multi-wavelength transport environment. This label switching normally occurs on a packet-by-packet basis. Typically, however, a large number of packets will be sequentially transported towards the same destination. This is especially true for bursty data where a large block of data is segmented in many packets for transport. In such cases, it is inefficient for each particular network element to carefully examine each label and decide on the routing path. Rather, it is more effective to set up a "virtual circuit" from the source to the destination. Header **210** of each packet will only inform continuation or ending of the virtual circuit, referred to as a flow state connection. Such an end-to-end flow state path is established, and the plug-and-play modules in the network elements will not disrupt such flow state connections until disconnection is needed. The disconnection will take place if such a sequence of packets have come to an end or another packet of much higher priority requests disruption of this flow state connection.

The priority aspect of the present invention is also shown with respect to FIG. **6**. The local look-up table has a "priority level" (column **613**) which sets forth the priority assigned to the label-switching state. Also, header **210** has appended priority data shown as the number '2' (reference numeral **616**). Both the fourth and fifth row in the "label-switch state" column **611** of table **610** have a local address of '0111.' If an earlier data packet used the entry in the fifth row to establish, for example, a virtual circuit or flow switching state, and the now another packet is processed as per the fourth row of column **611**, the higher priority data ('2' versus '4', with '1' being the highest) has precedent, and the virtual circuit would be terminated.

Detailed Illustrative Embodiments

In order to achieve ultra-low latency IP over WDM label switching, processing of the optical header at each optical

switch must be kept to a minimum during the actual transmission of the optical packet. To achieve this end, a new signaling architecture and packet transmission protocol for performing optical WDM label switching is introduced.

The signaling and packet transmission protocols decouple the slow and complex IP routing functions from the ultra-fast WDM switching and forwarding functions. This decoupling is achieved via the setup of an end-to-end routing path which needs to be performed very infrequently. To send IP packets from a source to a destination, the following step is executed in accordance with the present invention: optical packet transmission, where the arrival of the optical packet triggers the local header processing which among other things looks up the output port for forwarding the packet on to the next hop based on the optical label inside the optical header.

Although routing path setup involves invoking the routing function which is generally a slow and complicated procedure, it is performed prior to packet transmission handling, and hence it is not in the critical path that determines transmission latency.

Routing Path Setup

During routing path setup, the internal connection table of a WDM packet switch will be augmented with a label-switch look-up table, and contains the pertinent packet forwarding information. In particular, in the interest of achieving ultra-low latency and hardware simplicity, the inventive scheme produces label-switch states that remain constant along the flow path. For example, label-switch assignments include the following techniques:

(1) Destination-based flow label assignment—In this scheme the destination, e.g. a suitable destination IP address prefix can be used as the label-switch state in next hop look-up. In addition to having no need to modify the optical header, the same header can be used in the event of deflection routing.

(2) Route-based flow label assignment—In this scheme the label-switch state assigned refers to the end-to-end route that is computed dynamically at the label-switch state setup phase. The advantage of this scheme is that it can be specialized to meet the Quality-of-Service requirements for each individual label-switched states.

Switching Conflict Resolution

The present-day lack of a viable optical buffer technology implies that conventional buffering techniques cannot be used to handle switching conflicts. As previously described, the invention embodiment utilizes fixed delay implemented by an optical fiber to allow switching to occur during this time delay, but not to achieve contention resolution as electrical buffers do in conventional IP routers. To resolve switching contentions, in accordance with the present invention, the following three methods are used:

(a) Limited wavelength interchange —where a packet is routed through the same path but at a different wavelength. Since this wavelength conversion is utilized just to avoid the contention, it is not necessary that the network elements must possess the capability of converting to any of the entire wavelength channels. Rather, it is sufficient if they can convert some of the entire wavelength channels. This wavelength conversion converts both the signaling header and the data payload. Care must be taken to prevent a packet from undergoing too many wavelength conversions which will result in poor signal fidelity. A possible policy is to allow only one conversion, which and can easily be enforced by encoding the original wavelength in the optical header. This way an intermediate WDM switch will allow conversion if and only if it is carried on its original wavelength.

(b) Limited deflection routing—where a packet may be deflected to a neighboring switching node from which it can be forwarded towards its destination. Care again must be taken to prevent a packet from being repeatedly deflected, thereby causing signal degradation, as well as wasting network bandwidth. A solution scheme is to record a "timestamp" field in the optical header, and allow deflections to proceed if and only if the recorded timestamp is no older than a maximum limit.

(c) Prioritized packet preemption—where a newly arrived packet may preempt a currently transmitting packet if the arriving packet has a higher priority. The objective is to guarantee fairness to all packets so that eventually a retransmitted packet can be guaranteed delivery. In this scheme, each packet again has a timestamp field recorded in its optical header, and older packets have higher priority compared to newer packets. Furthermore a retransmitted packet assumes the timestamp of the original packet. This way, as a packet "ages," it increases in priority, and will eventually be able to preempt its way towards its destination if necessary.

It is noted that in all these schemes the optical header can remain constant as it moves around in the network. This is consistent with the desire to keep the optical switching hardware fast and simple. It is also possible to consider combinations of these schemes.

Routing Protocol

For a network the size of the NGI, centralized routing decisions are quite unfeasible, so the approach needs to be generalized to distributed decision making. Hierarchical addressing and routing are used as in the case of IP routing. When a new connection is requested, NC&M **220** decides whether a WDM path is provisioned for this (source, destination) pair within the WDM-based network. If it is, the packets are immediately sent out on that (one-hop IP-level) path. If no such path is provisioned, NC&M **220** decides on an initial outbound link for the first WDM network element and a wavelength to carry the new traffic. This decision is based on the rest of the connections in the network at the time the new connection was requested. NC&M **220** then uses signaling, through an appropriate protocol, to transfer the relevant information to the initial WDM network element to be placed in the signaling header. After the initial outbound link is determined, the rest of the routing decisions are taken at the individual NE's according to the optical signaling header information. This method ensures that the routing tables at each switching node and the signaling header processing requirements are kept relatively small. It also enables the network to scale easily in terms of switching nodes and network users. It is noted, too, that multiple WDM subnetworks can be interconnected together and each subnetwork will have its own NC&M.

When a path is decided upon, within a WDM NE, the optical switches can be set in that state (i) for the duration of each packet through the node and then revert back to the default state (called optical label-switching), or (ii) for a finite, small amount of time (called flow switching). The former case performs routing on a regular packet-by-packet basis. The system resources are dedicated only when there is information to be sent and at the conclusion of the packet, these resources are available for assignment to another packet. The latter case is used for large volume bursty mode traffic. In this case, the WDM NE only has to read a flow state label from the optical signaling header of subsequent packets arriving at the NE to be sure such packet is bound for the same destination, without the need to switch the switching device, and forward the payload through the

already existing connection through the NE as previously established by the optical label-switching.

The packets are self-routed through the network using the information in the signaling header of each packet. When a packet arrives at a switching node, the signaling header is read and either the packet is forwarded immediately through an already existing flow state connection or a new appropriate outbound port is chosen according to the routing table. Routing tables in each node exist for each wavelength. If the packet cannot follow the selected outbound port because of contention with another packet (the selected outbound fiber is not free), the routing scheme will try to allocate a different wavelength for the same outbound port (and consequently the signal will undergo wavelength translation within the switching node). If no other eligible wavelength can be used for the chosen outbound port, a different outbound port may be chosen from another table, which lists secondary (in terms of preference) outbound links.

This routing protocol of the inventive technique is similar to the deflection routing scheme (recall the Background Section), where the session is deflected to some other outbound link (in terms of preference) if the preferred path cannot be followed. The packet is not allowed to be continuously deflected. In traditional routing protocols, a hop count is used to block a session after a specified number of hops. In the new scheme, in case no header regeneration is allowed at the switching nodes, then the hop count technique cannot be used. Alternatively, the optical signaling header characteristics (i.e., the signaling header's SNR) can be looked upon to decide whether a packet should be dropped.

IP Routing Algorithm in WDM Layer

The technique used by NC&M **220** to determine the routing tables is based upon shortest path algorithms that route the packets from source to destination over the path of least cost. Specific cost criteria on each route, such as length, capacity utilization, hop count, or average packet delay can be used for different networks. The objective of the routing function is to have good performance (for example in terms of low average delay through the network) while maintaining high throughput. Minimum cost spanning trees are generated having a different node as a root at each time, and the information obtained by these trees can then be used to set-up the routing tables at each switching node. If deflection routing as outlined above is implemented, the k-shortest path approach can be used to exploit the multiplicity of potential routing paths. This technique finds more than one shortest path, with the paths ranked in order of cost. This information can be inputted into the switching node routing tables, so that the outbound link corresponding to the minimum cost path is considered first, and the links corresponding to larger cost paths are inputted in secondary routing tables that are used to implement deflection routing.

Description of Plug-and-Play Modules

The present invention is based upon two types of Plug-and-Play modules to be attached to the WDM network elements. Introduction of these Plug-and-Play modules add optical label switching capability to the existing circuit-switched network elements.

In FIG. **3**, both header encoder **321** and header remover **322** were shown in high-level block diagram form; FIGS. **7** and **8** show, respectively, a more detailed schematic for both encoder **321** and remover **322**.

In FIG. **7**, IP packets or datagrams are processed in microprocessor **710** which generates each optical signaling header **210** for label switching. Optical signaling header **210** and the original IP packet **211** are emitted from microprocessor **710** at baseband. Signaling header **210** is mixed in RF mixer **720** utilizing local oscillator **730**. Both the mixed header from mixer **720** and the original packet **211** are combined in combiner **740** and, in turn, the output of combiner **740** is encoded to an optical wavelength channel via optical modulator **760** having laser **750** as a source of modulation.

In FIG. **8**, the optical channel dropping out of a network element is detected by photodetector **810** and is electrically amplified by amplifier **820**. Normally, both photodetector **810** and the amplifier **820** have a frequency response covering only the data payload but not the optical signaling header RF carrier frequency provided by local oscillator **730**. Low-pass-filter **830** further filters out any residual RF carriers. The output of filter **830** is essentially the original IP packet sent out by the originating IP router from the originating network element which has been transported through the network and is received by another IP router at another network element.

Block diagram **900** of FIG. **9** depicts the elements for the detection process effected by Plug-and-Play module **410** of FIG. **4** to convert optical signal **901**, which carries both label-switching signaling header **210** and the data payload **211**, into baseband electrical signaling header **902**. Initially, optical signal **901** is detected by photodetector **910**; the output of photodetector **910** is amplified by amplifier **920** and filtered by high-pass filter **930** to retain only the high frequency components which carry optical signaling header **210**. RF splitter **940** provides a signal to local oscillator **950**, which includes feedback locking. The signal from local oscillator **950** and the signal from splitter **940** are mixed in mixer **960**, that is, the high frequency carrier is subtracted from the output of filter **920** to leave only the information on label-switching signaling header **210**. In this process, local oscillator **950** with feedback locking is utilized to produce the local oscillation with the exact frequency, phase, and amplitude, so that the high frequency component is nulled during the mixing of this local oscillator signal and the label-switching signaling header with a high-frequency carrier. Low-pass filter **970**, which is coupled to the output of mixer **960**, delivers baseband signaling header **210** as electrical output signal **902**.

The circuit diagram of FIG. **10** shows an example of a more detailed embodiment of FIG. **4**. In FIG. **10**, each header detector **1010**, **1020**, . . . , **1030**, . . . , or **1040** processes information from each wavelength composing the optical inputs arriving on paths **1001**, **1002**, **1003**, and **1004** as processed by demultiplexers **1005**, **1006**, **1007**, and **1008**, respectively; each demultiplexer is exemplified by the circuit **900** of FIG. **9**. The processed information is grouped for each wavelength. Thus, for example, fast memory **1021** receives as inputs, for a given wavelength, the signals appearing on lead **1011** from header detector **1010**, . . . , and lead **1034** from header detector **1030**. Each fast memory **1021–1024**, such as a content-addressable memory, serves as an input to a corresponding label switch controller **1031–1034**. Each label switch controller **1031–1034** also receives circuit-switched control signals from network element switch controller **420** of FIG. **4**. Each label switch controller intelligently chooses between the circuit switched control as provided by controller **420** and the label switched information supplied by its corresponding fast memory to provide appropriate control signals the switching device **430** of FIG. **4**.

Flow diagram **1100** of FIG. **11** is representative of the processing effected by each label-switch controller **1031–1034**. Using label-switch controller **1031** as exemplary, inputs from circuit-switched controller **420** and

inputs from fast memory **1021** are monitored, as carried out by processing block **1110**. If no inputs are received from fast memory **1021**, then incoming packets are circuit-switched via circuit-switched controller **420**. Decision block **1120** is used to determine if there are any inputs from fast memory **1021**. If there are inputs, then processing block **1130** is invoked so that label-switch controller **1031** can determine from the fast memory inputs the required state of switching device **430**. Then processing block **1160** is invoked to transmit control signals from label-switch controller **1031** to control switching device **430**. If there are no fast memory inputs, then the decision block **1140** is invoked to determine if there are any inputs from circuit-switched controller **1140**. If there are inputs from circuit-switched controller **420**, then processing by block **1150** is carried out so that label-switch controller **1031** determines from the inputs of circuit-switched controller **420** the required state of switching device **430**. Processing block **1160** is again invoked by the results of processing block **1150**. If there are no present inputs from circuit-switched controller **1140** or upon completion of procession block **1160**, control is returned to processing block **1110**.

By way of reiteration, optical label-switching flexibly handles all types of traffic: high volume burst, low volume burst, and circuit switched traffic. This occurs by interworking of two-layer protocols of the label-switched network control. Thus, the distributed switching control rapidly senses signaling headers and routes packets to appropriate destinations. When a long stream of packets reach the network element with the same destination, the distributed switching control establishes a flow switching connection and the entire stream of the packets are forwarded through the newly established connections.

A label switching method scales graciously with the number of wavelengths and the number of nodes. This results from the fact that the distributed nodes process multi-wavelength signaling information in parallel and that these nodes incorporate predicted switching delay in the form of fiber delay line. Moreover, the label switching utilizes path deflection and wavelength conversion for contention resolution.

Optical Header Processing

The foregoing description focused on optical header processing at a level commensurate with the description of the overall NGI system configured with the overlaid Plug-and-Play modules. Discussion of header processing at a more detailed level is now appropriate so as to exemplify how low-latency can be achieved at the circuit-detail level. To this end, the arrangement of FIG. **12**, which is a more detailed block diagram encompassed by the earlier descriptions of FIGS. **9** and **10** especially, is considered. As seen in FIG. **12**, optical signal **1001** serves as an input to demux **1005**, both of which are re-drawn from FIG. **10**. Furthermore, a detailed illustrative embodiment of header detector **1010** of FIG. **10** is now shown in FIG. **12**. In particular, header detector **1010** includes in this embodiment: (a) dispersion compensator **1205** for correcting dispersion in the optical signal at optical wavelength λ_1 emanating from demux **1005**; (b) optical-electrical converter **1210** (e.g., a photodetector) for producing electrical output signal **1211** from the optical signal departing compensator **1205**; (c) a bank of local oscillators having frequencies f_1, f_2, . . . , f_N feeding multipliers **1221**, **1231**, . . . , **1241**, respectively, for frequency-shifting the frequency components of electrical signal **1211** to intermediate frequencies (IFs); (d) a bank of IF band-pass-filters (IF-BPF) **1222**, **1232**, . . . , **1242** responsive to multipliers **1221**, **1231**, . . . , **1241**, respectively, to filter the frequency domain energy in header signals **1213**, . . . , **1215** shown at the top left-hand of FIG. **12**; (e) a cascade of envelope detector/decision circuit pairs **1223/1224**, **1233/1234**, . . . , **1243/1244** wherein the presence of frequency domain energy in any of the frequency bands centered at f_1, f_2, . . . , f_N is denoted as a logic '1' at the output of the decision circuits **1224**, **1234**, . . . , **1244**, whereas the absence of frequency domain energy at f_1, f_2, . . . f_N is denoted as a logic '0'; (f) logic circuit **1250** which provides a switch selection signal on selection lead **1260**, the function of which being discussed in more detail in the operational description below; (g) delay circuits **1225**, **1235**, . . . , **1245** coupled to the BPF filters **1222**, . . . , **1242**; (h) switches **1261**, **1262**, . . . , **1263**, coupled to delay circuits **1225**, . . ., **1245** as inputs, and being controlled by the signal on lead **1260**; (g) input lead **1265**, connected to switches **1261**, . . . **1263**, which serves as an input to demodulator **1291**; (h) detector **1292** responsive to demodulator **1291**; and (i) read circuit **1293** which outputs signal **1011** of FIG. **10**.

The operation of header detector **1010** of FIG. **12** is as follows. It is assumed that the second type of 'Plug-and-Play' module of FIG. **4** injects a 2.5 Gbps IP data packet (e.g., with QPSK/QAM modulation) which is sub-carrier multiplexed with a 155 Mbps header packet (e.g., with QAM modulation) at a center frequency f_1 ; as before, the header precedes the data payload in time and both are both carried by the optical wavelength λ_1. In each network node which receives the combined header and payload at wavelength λ_1, the sub-carrier header at λ_1 is detected by envelope detector **1212**. Because there is energy present in the frequency band centered at λ_1 due to the existence of the header signal, decision circuit **1224** detects a logic '1', whereas all other decision circuits detect a logic '0'. This combination of logic signals ('100 . . . 0') in parallel at the input to logic circuit **1250** generates the selection signal **1260** which effects the closure of only switch **1261**. (It is important to emphasize that the input logic signals are generated concurrently and in parallel, rather than in series, thereby significantly speeding up the header detection process.) The actual header signal provided at the output of IF-BPF **1222** serves, after the delay imposed by delay circuit **1225**, as the input to demodulator **1291** via lead **1265**. The delay of circuit **1225** is not critical, other than the delay is greater than the time required to derive the logic signal via envelope detector **1223** and decision circuit **1224**, plus the time required to compute the control signal on selection signal lead **1260** in logic circuit **1250** and to close switch **1261**. (The delay can be implemented digitally, e.g., by replacing each analog delay in FIG. **12** by a cascade of a demodulator and a digital delay.) Therefore, the header signal at f_1 is the only header signal that will be demodulated by demodulator **1291** (e.g., a QAM demodulator), and the demodulated baseband data burst is then detected by detector **1292** (e.g., a 155 Mbps burst-mode receiver), and read by circuit **1293** (e.g., a microprocessor).

This foregoing operational description has focused only on the detection of the optical header to control the routing path through switching device **430** of FIG. **4**. As alluded to in the Background Section, header replacement is now considered important to present-day NGI technology so as to accomplish high-throughput operation in a packet switched network in which data paths change due to, for example, link outages and variable traffic patterns. Moreover, header replacement is useful to maintain protocol compatibility. The components of FIG. **12** which have heretofore not been described play a central role in header replacement. Actually, the notion of header replacement has a broader

connotation in that the header may be composed of various fields, such as a "label" field and a "time-to-leave" field. The description to this point has used the header and label interchangeably; however, it is now clear that the header may actually have a plurality of fields, and as such any or all may be replaced at any node.

Now continuing with the description of FIG. **12**, it is shown that logic circuit **1250** also provides a second selection signal on selection lead **1270**; this lead control switches **1271, 1272, . . . , 1273** which are all connected to lead **1295**. Interposed between lead **1295** and header output lead **1011** is write circuit **1294** in cascade with modulator **1296**. Write circuit **1294** is responsible for providing a new header signal. The header signal that arrives at the input to demux **1005** is referred to as the active header signal—in the first node to process the header signal, the active header signal and the original header signal coalesce. The new header signal, rather than actually overwriting the active header signal, is placed in a frequency band above the frequency band of the active header signal, that is, the next highest available center frequency from the set $f_1, f_2, \ldots, f_N$ is utilized to propagate the new header signal. To select the next highest available center frequency, logic circuit **1250** is arranged so that if decision circuits **1224, 1234, . . . , 1244** yield an active center frequency f_i, then selection signal **1270** will close only the switch from the set **1271, 1272, . . . , 1273** which connects lead **1295** to center frequency f_{i+1}. That is, lead **1295** will be connected to the multiplier from the set **1281, 1282, . . . , 1283** which corresponds to frequency f_{i+1}. The outputs of multipliers **1281, 1282, . . . , 1283** are connected to lead **1284**, which serves as a second input to optical switch/add-drop multiplexer **1207**; the other input is provided by the header signal on lead **1011**. Circuit **1207** now has a dual functionality, namely, it operates as switching device **430** of FIG. **4**, but is also arranged to convert an input electrical signal, such as on lead **1284**, to an optical signal for propagation by the same optical wavelength present at the input to circuit **1207** (in this case, wavelength λ_1). Accordingly, the new header signal on lead **1284** is frequency shifted above the data payload as well as all other existing headers arriving on lead **1208**; this is shown in frequency domain visualization in the top right-hand corner of FIG. **12**, which is counterpart of the visualization in the top left-hand corner. So that the new header signal is placed ahead of the data payload in time, delay is introduced by fiber loop **1206**.

The operation of the arrangement of FIG. **12** for header replacement is as follows. Again, the same example is used so that an optical header plus a data payload is incoming to the network node immediately following the node that injected the packet. It is desired to write a new header signal, and in the embodiment of FIG. **12**, the output of read circuit **1293** serves as an input to write circuit **1294**; in this manner, the active header signal may serve as an aid in computing the new header signal. The new header signal is conveyed by center frequency f_2 since the incoming active header signal is centered about f_1. In effect, the new header signal is written on the original light which contains both the data packet and the old sub-carrier header or active header signal at f_1. Therefore, the modulated light which leaves the given node contains the data packet and two sub-carrier header signals. (Two illustrative writing techniques, both of which use a high-speed (~10 GHz) $LiNbO_3$-based modulator/switch, will be explained later.) The carrier frequency f_2 is higher than f_1 by about 200 MHz for the 155 Mbps data, but the frequency difference between f_1 and f_2 can be smaller if a more spectral efficient modulation method such as M-QAM is adopted. Note that this node has the intelligence via logic circuit **1250** to know that the active header signal uses sub-carrier f_1 and the new header signal is written onto sub-carrier f_2.

In a similar manner, the third network node along the route will read the active header signal on sub-carrier f_2 and write a new header information onto subcarrier f_3, and the process continues until the modulation bandwidth of optical switch/ADM **1207** is exhausted. For example, a typical 10 GHz external $LiNbO_3$-based modulator/switch can write about 40 ((10-2)/0.2) new sub-carrier headers signals, where it has been assumed that the 2.5 Gbps data occupies a bandwidth of 2 Ghz.

FIG. **12** actually illustrates the implementation details of the fourth network node along the route over which a packet travels. The three sub-carrier headers on λ_1 are simultaneously down-converted to IF band, and due to their existence, decision circuits **1224, 1234, . . . , 1244** generate a logic '1' signal to logic circuit **1250** in the pattern "111000 . . . 000". Note that if there are 40 down-converters in this example, **37** decision circuits will generate logic '0s" because there are no sub-carriers on $f_4, f_5, \ldots f_{40}$. Logic circuit **1250** uses the output "1110000 . . . 0" (three ones and thirty-seven zeros) to control the 40 microwave switches **1261, 1262, . . ., 1263** such that only the third microwave switch is closed and all other 39 switches are open. Therefore, the header information on f_3 becomes the active header signal that is then demodulated by demodulator **1291**. Immediately after the "read" process, the new header signal is generated by write circuit **1294** and then applied to modulator **1296** at IF. As depicted in FIG. **12**, the new header signal is launched to the fourth microwave switch which is turned on by selection signal **1270**. The new header signal is then up-converted by f_4, and is used to modulate the delayed main-path signal on optical path **1208** (which originally contains only three sub-carrier headers). The resultant modulated light therefore contains four sub-carrier headers as depicted.

It is noted that, in terms of presently available components, the processing time of the envelope detectors (**1223, . . .**), the decision circuits (**1224, . . .**), the logic circuit (**1250**), and the turning-on of a particular microwave switch (**1261, . . .**) should take less than 30 ns. On the other hand, if it is assumed that there are 15 bits in each packet header signal, then the time to read 15 bits, write 15 bits, and add 10 preamble bits can take about 260 ns for a 155 Mbps burst. Therefore, allowing for some variations, each header signal is about 300 ns. This means that the length of delay line **1206** in main optical path **1208** should be around 60 meters.

There exist some upper bounds on the proposed sub-carrier header insertion technique of FIG. **12**: (a) the sub-carriers at carrier frequencies as high as 10 GHz can become severely attenuated due to fiber dispersion after a certain transmission distance (usually tens of kilometers). Fortunately, this problem can be solved by repeatedly using dispersion compensation fibers (such as compensator **1205**) or chirped fiber gratings at every network node; (b) at each intermediate network node, its modulator **1296** (e.g., a $LiNbO_3$-based modulator) modulates the incoming "modulated" light by a new sub-carrier header signal, and this can cause new intermodulation distortion products. However, the present technology is such that the nonlinear distortion penalty after 40 times of writing consecutive sub-carrier header signals is not large enough to degrade the bit-error-ratio (BER) of both the data payload and the sub-carrier header signal up to a distance of 2000 km; and (c) since the

maximum number of insertable sub-carrier header signals are about 40 using a 10 GHz modulator, at some point in the network the entire sub-carrier header signals will have to be erased so that a new set of sub-carrier header signals can be written onto the received light all over again. Being conservative, it is determined that the maximum transmission distance using the arrangement of FIG. **12** is about 2000 km. Therefore, it is feasible that several "reset" network nodes are implemented, configured as shown in FIG. **13**, which are sparsely located across the nation, to guarantee that the 40 times-writing limit is never exceeded. It is noted, however, that not every node will insert a new header signal (recall the new header signal is typically inserted due to slowly varying network outages or for protocol compatibility). If this is indeed the case, then it is anticipated that 40 header signal insertions are more than enough to cover any cross-nation transport of an optical packet.

However, to be sure that a new header signal can be inserted when needed, preferably some or even all of the network nodes are arranged with the circuitry **1300** of FIG. **13**. The primary difference between FIGS. **12** and **13** is in the upper path of FIG. **12** wherein the main-path optical signal appearing at the output of compensator **1205** is converted back to electrical domain via opto-electrical converter **1210**, with all of its old sub-carrier header signals being erased by using low-pass filter (LPF) **1311**. A new, single sub-carrier header signal centered at frequency f_1 is added to the regenerated data payload in electrical adder **1313**; the data payload is regenerated in the conventional electrical manner by timing recovery-and-decision circuitry **1312**. Together the data payload and new header signal modulate electrical-optical transmitter **1314** having the same wavelength λ_1. Therefore, from this reset node on, another 40 sub-carrier header signals can be written before there is the (unlikely) need to reset again.

Another Illustrative Embodiment of a Header Insertion Technique

The circuit arrangements of FIGS. **12** and **13** were realized without the need for local light injection. In order to increase the transmission distance beyond the anticipated 2000 km limit, another node header processing arrangement is required, as now depicted in FIG. **14**; this arrangement deploys the injection of local light at wavelength λ_1. The main difference between FIGS. **12** and FIG. **14** is shown the processing path composed of the following components: (a) opto-electrical converter **1410**; (b) decision circuit **1440** responsive to converter **1410**; (c) the series arrangement of delay line **1411** and optical gate **1420**, with delay line **1411** being responsive to the output of compensator **1205**; (d) coupler **1430** responsive to gate **1420**; (e) light feedback path **1431** for feeding output light from coupler **1430** to its input, path **1431** being composed of erbium-doped fiber amplifier (EDFA) **1432** and optical switch **1433**; (f) light modulator **1450** responsive to the electrical signal appearing on path **1284**, as before; and (g) optical adder **1460** responsive to both light modulator **1450** and optical switch/ADM **1207**. An augmented optical packet **1470**, with the form shown in the lower left corner of FIG. **14**, now arrives at the network node of FIG. **14** via optical path **1001**. Preamble **1471** in optical packet header **1470**, after optical-to-electrical conversion in opto-electrical converter **1410**, directs detection circuit **1440** to turn on optical gate **1420** and let short CW light burst **1472** (about 30 ns in duration) at λ_1 pass through to coupler **1430**. CW light burst **1472** then loops several times via feedback path **1431** to lengthen the CW light duration to about 300 ns; this extended duration CW burst serves as an input to light modulator **1450** via output path **1451** from coupler **1430**. The new sub-carrier header signal appearing on lead **1284** then modulates this locally regenerated CW light burst on lead **1452** via light modulator **1450** (e.g., via a $LiNbO_3$ modulator). The modulated light which appears on output lead **1452** of light modulator **1450**, containing only the new, active sub-carrier header signal, is then combined in optical adder **1460** along with the main-path light which contains the data payload and the old sub-carrier header signals as emitted by switch **1207**. The time of occurrence of the new sub-carrier header signal arrives essentially concurrently with original optical packet **1470** at optical adder **1460**. (In an intermediate network node, it is important for the node to re-modulate the new header onto the original wavelength in the same time frame as the payload data.) Thus the light pulse conveying the new active header signal occupies the same time interval as the incoming header signals **1473**, with the difference being that the old header signals and the new active header signal are separated in the frequency domain by their corresponding sub-carrier frequencies. That is, each time a new header signal is added, the light conveying the new header signal at the given wavelength λ_1 is overlaid on the incoming light signal conveying the old header signals, but being such that the frequency domain characteristics are determined by the sub-carrier frequencies.

With this technique, no additional nonlinear distortions are generated due to the modulation of an already modulated light. As long as the optical power ratio between the main-path light from switch **1207** and the locally-injected light from light modulator **1450** is optimized, and the modulation depths of the sub-carrier headers and data payload are optimized, transmission can be beyond 2000 km is effected.

An Alternative Header Replacement Technique

It is also possible to use an optical notch filter which has a very high finesse to notch out the old sub-carrier header signal. The network node configuration **1500** is shown in FIG. **15**; it is readily appreciated that node configuration **1500** is greatly simplified relative to the implementation of FIG. **12**. The sub-carrier header signal at centered at f_N is purposely allocated at high-frequency carrier (e.g., 9 GHz) so that the header signal conveyed f_N will not affect the data payload in the low frequency region. The output of compensator **1205** feeds optical circulator **1510**, which is coupled to fiber Fabry-Perot (FFP) notch filter **1515** and attenuator **1520** in series. The combined effect of these components is to notch out the header signal centered at f_N; the spectrum of the input to optical circulator **1510** is shown in the top left corner, whereas the spectrum of the output of circulator **1510** is shown in the top center. The newly inserted header signal is provided by the series combination: write circuit **1294**; modulator **1296**; up-converter **1281** being driven by sub-carrier f_N, in a much simplified manner as that of FIG. **12**.

Optical Technology

Optical technologies span a number of important aspects realizing the present invention. These include optical header technology, optical multiplexing technology, optical switching technology, and wavelength conversion technology.

(a) Optical Header Technology

Optical header technology includes optical header encoding and optical header removal as discussed with respect to FIGS. **3** and **4**. In effect, optical header **210** serves as a signaling messenger to the network elements informing the network elements of the destination, the source, and the length of the packet. Header **210** is displaced in time compared to the actual data payload. This allows the data payload to have any data rates/protocols or formats.

(b) Optical Multiplexing Technology

Optical multiplexing may illustratively be implemented using the known silica arrayed waveguide grating structure. This waveguide grating structure has a number of unique advantages including: low cost, scalability, low loss, uniformity, and compactness.

(c) Optical Switching Technology

Fast optical switches are essential to achieving packet routing without requiring excessively long fiber delay as a buffer.

Micromachined Electro Mechanical Switches offer the best combination of the desirable characteristics: scalability, low loss, polarization insensitivity, fast switching, and robust operation. Recently reported result on the MEM based Optical Add-Drop Switch achieved 9 microsecond switching time

(d) Wavelength Conversion Technology

Wavelength conversion is resolves packet contention without requiring path deflection or packet buffering. Both path deflection and packet buffering cast the danger of skewing the sequences of a series of packets. In addition, the packet buffering is limited in duration as well as in capacity, and often requires non-transparent methods. Wavelength conversion, on the other hand, resolves the blocking by transmitting at an alternate wavelength through the same path, resulting in the identical delay. Illustratively, a WSXC with a limited wavelength conversion capability is deployed.

Although various embodiments which incorporate the teachings of the present invention have been shown and described in detail herein, those skilled in the art can readily devise many other varied embodiments that still incorporate these teachings.

What is claimed is:

1. A method for propagating a data payload from an input network element to an output network element in a wavelength division multiplexing (WDM) network composed of a plurality of network elements, the data payload having a given format and protocol, the method comprising the steps of

generating and storing a local routing look-up table in each of the network elements, each local routing table determining alternative local routes through the associated one of the network elements,

adding a header to the data payload prior to inputting the data payload to the input network element to produce an optical signal, the header having a format and protocol and being indicative of the local route through each of the network elements for the data payload and the header, the format and protocol of the data payload being independent of the format and protocol of the header,

detecting the header at the network elements to produce a switch control signal as the data payload and header propagate through the WDM network,

selecting one of the local routes for routing the optical signal through each of the network elements as determined by looking up the switch control signal in the corresponding local routing table, and

routing the optical signal through the network elements in correspondence to the selected route,

wherein the header is composed of one or more header signals each being conveyed by a distinct sub-carrier frequency and arranged so that the highest detectable sub-carrier frequency corresponds to an active header signal, the plurality of sub-carrier frequencies occupying a frequency band above the data payload, the step of detecting including the steps of

concurrently measuring the header signals to produce a header selection signal,

selecting the active header signal as conveyed by the highest detectable sub-carrier frequency under control of the header selection signal, and

processing the active header signal to obtain the switch control signal for routing the optical signal.

2. The method as recited in claim 1 further including the step, executed prior to the step of concurrently measuring, of opto-electrically converting the optical signal to an electrical header conveying the active header signal.

3. The method as recited in claim 2 wherein the step of processing includes the step of demodulating the electrical header to obtain a demodulated active header signal.

4. The method as recited in claim 3 wherein the step of processing further includes the step, after the step of demodulating, of detecting header information in the demodulated active header signal.

5. The method as recited in claim 4 wherein the step of processing further includes the step, after the step of detecting the header information in the demodulated active header signal, of reading the header information to produce the switch control signal.

6. The method as recited in claim 5 wherein the step of reading includes the step of inputting the header information to a content-addressable memory to produce the switch control signal.

7. The method as recited in claim 1 further including the step, prior to the step of concurrently measuring, of opto-electrically converting the optical signal to an electrical header, and wherein the step of concurrently measuring includes the step of down-converting the electrical header to a plurality of intermediate frequency signals indicative of the header signals.

8. The method as recited in claim 7 wherein the step of down-converting includes the steps of locally generating the plurality of sub-carrier frequencies and multiplying the electrical header by the plurality of local sub-carrier frequencies to produce the plurality of intermediate frequency signals.

9. The method as recited in claim 8 further including the step, after the step of multiplying, of envelope detecting each of the intermediate frequency signals to concurrently produce a plurality of envelope-detected signals.

10. The method as recited in claim 9 further including the step, after the step of envelope detecting, of concurrently threshold detecting each of the envelope-detected signals to produce a plurality of decision signals.

11. The method as recited in claim 10 further including the step, after the step of threshold detecting, of inputting the plurality of decision signals to a logic circuit to produce the header selection signal.

12. A method for detecting a header in an optical signal propagating at a given wavelength, the optical signal including the header and a data payload, the header being composed of one or more header signals each being conveyed by a distinct sub-carrier frequency and arranged so that the highest detectable sub-carrier frequency corresponds to an active header signal, the plurality of sub-carrier frequencies occupying a frequency band above the data payload, the header containing header information for routing the optical signal through a switch, the method comprising the steps of

concurrently measuring the header signals to produce a header selection signal,

selecting the active header signal as conveyed by the highest detectable sub-carrier frequency under control of the header selection signal, and

processing the active header signal to produce a switch control signal to control the switch.

13. The method as recited in claim 12 further including the step, executed prior to the step of concurrently measuring, of opto-electrically converting the optical signal to an electrical header conveying the active header signal.

14. The method as recited in claim 13 wherein the step of processing includes the step of demodulating the electrical header to produce a demodulated active header signal.

15. The method as recited in claim 14 wherein the step of processing further includes the step, after the step of demodulating, of detecting the header information in the demodulated active header signal.

16. The method as recited in claim 15 wherein the step of processing further includes the step, after the step of detecting the header information, of reading the header information to produce the switch control signal.

17. The method as recited in claim 16 wherein the step of reading includes the step of inputting the header information to a content-addressable memory to produce the switch control signal.

18. The method as recited in claim 12 further including the step, prior to the step of concurrently measuring, of opto-electrically converting the optical signal to an electrical header, and wherein the step of concurrently measuring includes the step of down-converting the electrical header to a plurality of intermediate frequency signals indicative of the header signals.

19. The method as recited in claim 18 wherein the step of down-converting includes the steps of locally generating the plurality of sub-carrier frequencies and multiplying the electrical header by the plurality of local sub-carrier frequencies to produce the plurality of intermediate frequency signals.

20. The method as recited in claim 19 further including the step, after the step of multiplying, of envelope detecting each of the intermediate frequency signals to concurrently produce a plurality of envelope-detected signals.

21. The method as recited in claim 20 further including the step, after the step of envelope detecting, of concurrently threshold detecting each of the envelope-detected signals to produce a plurality of decision signals.

22. The method as recited in claim 21 further including the step, after the step of threshold detecting, of inputting the plurality of decision signals to a logic circuit to produce the header selection signal.

23. A method for inserting a header to propagate with an data payload both propagating by an optical signal at a given optical wavelength, the method comprising the steps of

generating a header signal at baseband with a predetermined frequency spectrum, the header signal being representative of the header,

frequency-shifting the header signal using a carrier frequency so that the frequency-shifted spectrum of the header signal is located above the frequency spectrum of the data payload,

adding the frequency-shifted header signal and the data payload to produce a combined signal, and

electro-optically converting the combined signal to generate the optical signal at the given wavelength.

24. A system for detecting a header in an optical signal propagating at a given optical wavelength, the optical signal including both the header and a data payload, the header being composed of one or more header signals each being conveyed by a distinct sub-carrier frequency and arranged so that the highest detectable sub-carrier frequency corresponds to an active header signal, the plurality of sub-carrier frequencies occupying a frequency band above the baseband spectrum of the data payload, the header containing header information for routing the optical signal through a switch, the system comprising

a measurement device for concurrently measuring the header signals to produce a header selection signal,

a selector, coupled to the measurement device, for determining the active header signal as conveyed by the highest detectable sub-carrier frequency under control of the header selection signal, and

a processor, coupled to the selector, for processing the active header signal to produce a switch control signal to control the switch.

25. The system as recited in claim 24 further including an opto-electrically converter, responsive to the optical signal, for converting the optical signal to an electrical header conveying the active header signal.

26. The system as recited in claim 25 wherein the processor further includes a demodulator for demodulating the electrical header to a demodulated active header signal.

27. The system as recited in claim 26 further including a baseband detector, responsive to the demodulator, for detecting header information in the demodulated active header signal.

28. The system as recited in claim 27 further including a reader, responsive to the baseband detector, for reading the header information to produce the switch control signal.

29. The system as recited in claim 28 further including a content-addressable memory and means, responsive to the reader, for inputting the header information to the content-addressable memory to produce the switch control signal.

30. The system as recited in claim 24 further including an opto-electrical converter, responsive to the optical signal, for converting the optical signal to an electrical header, and wherein the measurement device includes a down-converter for down-converting the electrical header to a plurality of intermediate frequency signals indicative of the header signals.

31. The system as recited in claim 30 wherein the down-converter includes a local generator for generating the plurality of sub-carrier frequencies and a multiplier, responsive to the local generator and the electrical header signal, for multiplying the electrical header by the plurality of local sub-carrier frequencies to produce the plurality of intermediate frequency signals.

32. The system as recited in claim 31 further including an envelope detector, responsive to the multiplier, for envelope detecting each of the intermediate frequency signals to concurrently produce a plurality of envelope-detected signals.

33. The system as recited in claim 32 further including a threshold detector, responsive to the envelope detector, for concurrently threshold detecting each of the envelope-detected signals to produce a plurality of decision signals.

34. The system as recited in claim 33 further including a logic gate, responsive to the threshold detector, for receiving the plurality of decision signals to produce the header selection signal.

35. A system for propagating a data payload from an input network element to an output network element in a wavelength division multiplexing (WDM) network composed of a plurality of network elements, the data payload having a given format and protocol, the system comprising

a route generator for generating and storing a local routing look-up table in each of the network elements, each local routing table determining alternative local routes through the associated one of the network elements,

an adder for adding a header to the data payload prior to inputting the data payload to the input network element to produce an optical signal, the header having a format and protocol and being indicative of the local route through each of the network elements for the data payload and the header, the format and protocol of the data payload being independent of the format and protocol of the header,

a detector for detecting the header at the network elements to produce a switch control signal as the data payload and header propagate through the WDM network,

a selector for selecting one of the local routes for routing the optical through the network elements as determined by looking up the switch control signal in the corresponding local routing table, and

a switch for routing the optical signal through the network elements in correspondence to the selected route,

wherein the header is composed of one or more header signals each being conveyed by a distinct sub-carrier frequency and arranged so that the highest detectable sub-carrier frequency corresponds to an active header signal, the plurality of sub-carrier frequencies occupying a frequency band above the data payload, the detector further comprising

a measurement device for concurrently measuring the header signals to produce a header selection signal,

a selector, coupled to the measurement device, for determining the active header signal as conveyed by the highest detectable sub-carrier frequency under control of the header selection signal, and

a processor, coupled to the selector, for processing the active header signal to produce the switch control signal to control the switch.

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